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For air-breathing hypersonic vehicles with scramjet engines, waverider-like forebodies are employed in order to reduce pressure leakage from the lower to upper surface and/or satisfy a shock-on-cowl lip condition to achieve superior inlet flow quality at a given design condition. However, any aeroelastic or dynamic perturbations will give rise to a non-ideal inlet flow field. This may induce vehicle instability in terms of the interaction of hypersonic aerodynamic, aeroelastic, aeroservoelastic, as well as aerothermoelastic interaction.

This STTR Phase II project is to develop a "Conceptual-Design/Analysis" (CDA) tool for precisely the purpose of rapid assessment of vehicle stability and control law implementation. Resulting ASTPE package includes Aero-Servo-Thermo-Propulso-Elasticity disciplines and a Graphical User Interface (GUI) has been created to assist driving individual modules in ASTPE package. Case studies include Single Engine Missile (SEM) and Single Engine Demonstrator (SED).

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Scramjet; Multi-Disciplinary Optimization Design Tool; Aero-Servo-Thermo-Propulso-Elasticity; SEM; SED; Conceptual-Design/Analysis

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Integrated Aero-Servo-Thermo-Propulso-Elasticity (ASTPE) for Hypersonic Scramjet Vehicle Design/Analysis

STTR PHASE II Contract No. FA9550-07-C-0043

FINAL REPORT

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ZONA TECHNOLOGY

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Abstract

For air-breathing hypersonic vehicles with scramjet engines, waverider-like forebodies are employed in order to reduce pressure leakage from the lower to upper surface and/or satisfy a shock-on-cowl lip condition to achieve superior inlet flow quality at a given design condition. However, any aeroelastic or dynamic perturbations will give rise to a non-ideal inlet flow field. This may induce vehicle instability in terms of the interaction of hypersonic aerodynamic, aeroelastic, aeroservoelastic, as well as aerothermoelastic interaction.

This STTR Phase II project is to develop a "Conceptual-Design/Analysis" (CDA) tool for precisely the purpose of rapid assessment of vehicle stability and control law implementation. Resulting ASTPE package includes Aero-Servo-Thermo-Propulso-Elasticity disciplines and a Graphical User Interface (GUI) has been created to assist driving individual modules in ASTPE package. Case studies include Single Engine Missile (SEM) and Single Engine Demonstrator (SED).

In this report, Chapter 1 provides background of this work, previous investigations and a brief introduction of ASTPE package. Chapter 2 ~ 7 give theoretical details of individual modules in ASTPE. Chapter 2 describes UCDA, which is a scramjet vehicle design and analysis code. In Chapter 3, UPTOP, a trajectory optimization code is presented. Chapter 4 documents TPSOPT, which is a Thermal Protection System (TPS) optimization program. SMB, a Structural Modal Base program, is included in Chapter 5. Chapter 6 and 7 describe implemented trim module and aeroservoelasticity module respectively. Case studies of SEM and SED are demonstrated in Chapter 8 and 9.

Chapter 1 Introduction

1.1 Background

Emerging hypersonic technology from space access and the global-strike vehicle to hypersonic Unmanned Air Vehicles (UAVs) demands effective hypersonic methodology for vehicle design and analysis. Air-breathing hypersonic vehicle concepts employing scramjet engines for cruise, space access, and hypersonic strike capabilities are currently being developed through several ongoing R&D efforts. Notably, these include the Waverider/Single Engine Demonstrator (WR-SED/X-51) by the Air Force, the Force Application and Launch from the Continental U.S. (FALCON) by DARPA, Hyper-X (X-43) by NASA (Figure 1.1), and HyFly by the Navy. Most of these designs take advantage of waverider or waverider-like forebodies to either minimize pressure leakage from the lower to upper surface and/or satisfy a shock-on-cowl lip condition to achieve superior inlet flow quality at a given design condition. However, any aeroelastic or dynamic perturbations will give rise to a non-ideal inlet flowfield. This would then induce vehicle instability in terms of the interaction of hypersonic aerodynamic, aeroelastic, aeroservoelastic, and propulsive forces, let alone the important aerothermoelastic interaction.

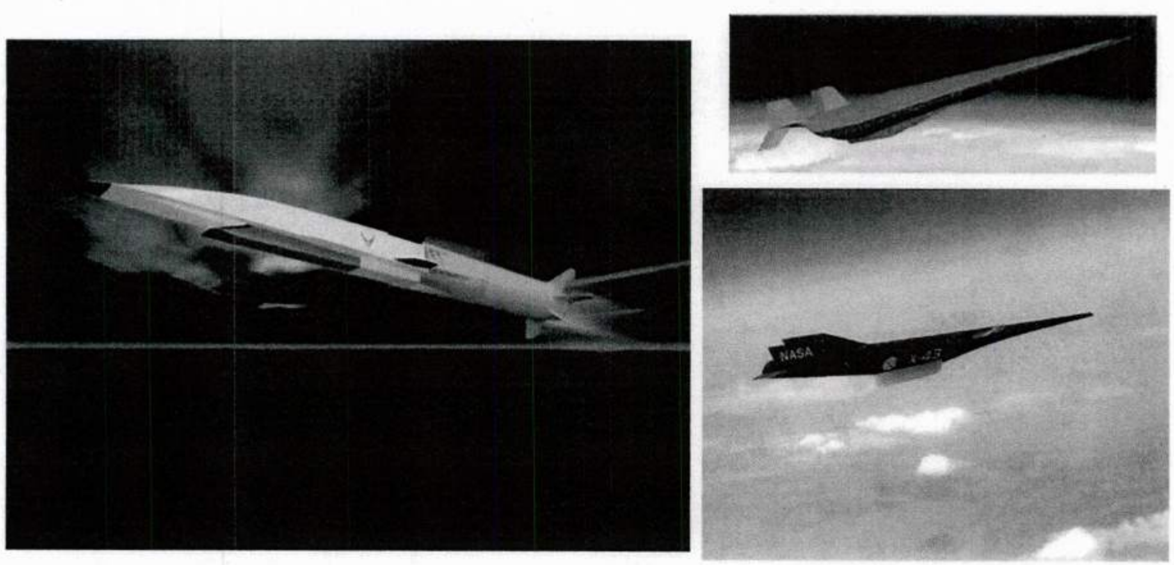


Figure 1.1 WaveRider-SED (X-51), FALCON and HyperX

To provide control to such types of instability in such extreme environments with aerothermal considerations is a challenging endeavor. McRuer [1.1] has warranted that the integration of airframe, propulsion, control, and dynamics should be a central issue for hypersonic vehicle design whereby forbidden zones appear in the hypersonic flight/operation corridor (bounded by the 1-g-upper and the thermal-load-lower boundaries) due to control limits as shown in Figure 1.2. Bowcutt [1.2] also ranked high the importance of the vehicle control system development for X-43s, HyFly and X-51.

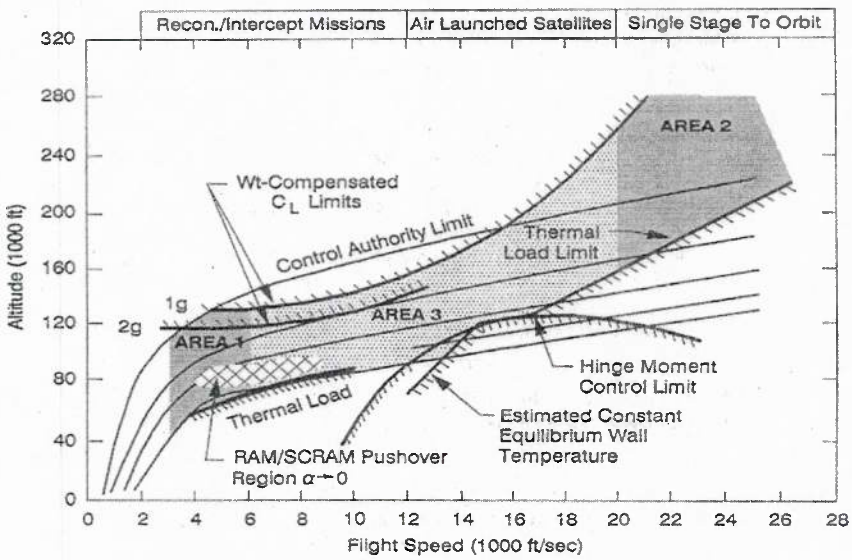


Figure 1.2 Excluded operational regions in flight corridor (taken from Ref. [1.1])

The development and optimization of hypersonic vehicles is a challenging endeavor with the design closure of missile-scale vehicles proving even more elusive. This complexity was extremely evident in NASA's Hyper-X program where there was a vast difference between the vehicle design scale and the scale of the flight test vehicle. The Boeing Dual-Fuel vehicle (shown in Figure 1.3) was designed as a Mach 10, 200 foot class, global reach cruise vehicle, but was photographically scaled down to 14 feet while preserving most of the original length scale of the scramjet engine to emerge as the NASA's Hyper-X, Mach 7 configuration (shown in Figure 1.4). The resulting vehicle then required silane to initiate and sustain combustion in the small-scale engine and utilized a 1000 pound block of tungsten in the forebody to balance the lift and moment. Clearly, the effort which goes into evolving and refining a complex, hypersonic vehicle design is substantial, especially when including the intricate synergy required between the

disciplines of aerodynamics, propulsion, aeroelasticity, stability and control, and aerothermodynamics.

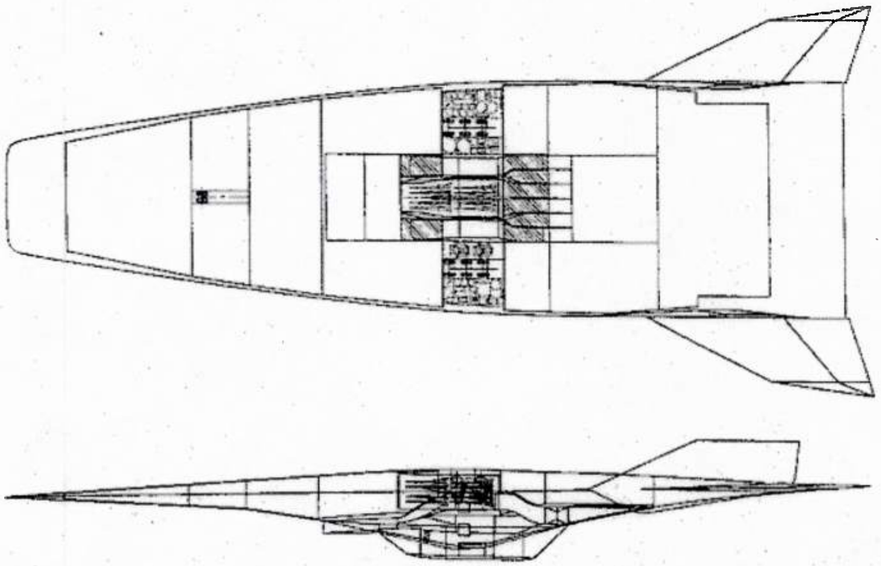


Figure 1.3 Boeing global reach, Mach 10, dual-fuel vehicle

The thought that some feel that it is better to use an existing vehicle as a baseline configuration rather than initiate the design process for a new mission and vehicle scale is troubling. It is in this area where our STTR Phase II research effort becomes essential; understanding the physics involved with many competing disciplines and developing an efficient vehicle design and optimization process. This is the original design philosophy and the approach of Starkey and Lewis [1.3]. Based on their work, the ZONA Team has developed some lower fidelity models in the interest of computational expense and understanding discipline trade-offs. Increasing the fidelity of the design tools for any given discipline can be done, as needed, in the future, but understanding the underlying process and intricate synergy must be made a priority.

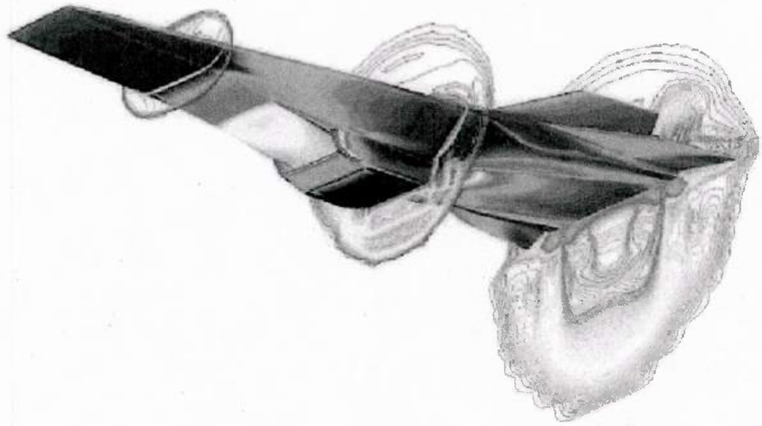


Figure 1.4 NASA's Mach 7 Hyper-X test vehicle

A baseline hypersonic vehicle geometry (in this case a missile configuration) and some of the design variables required are shown in Figure 1.5. In all, a vehicle of this type can be generated with as few as 20 design variables. Although increasing the number of design variables makes the optimization process more complex, modern day parallel processing techniques make this convergence achievable within a number of hours on a computer cluster. Due to the highly non-linear nature of the design variable interactions and disjoint design space, hybrid evolutionary/gradient optimization schemes are favored, as outlined in Figure 1.6.

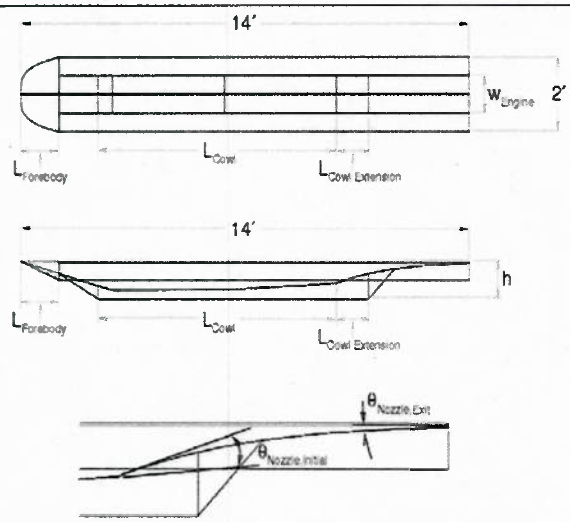


Figure 1.5. Waverider based, air-breathing hypersonic missile with some external design variables labeled.

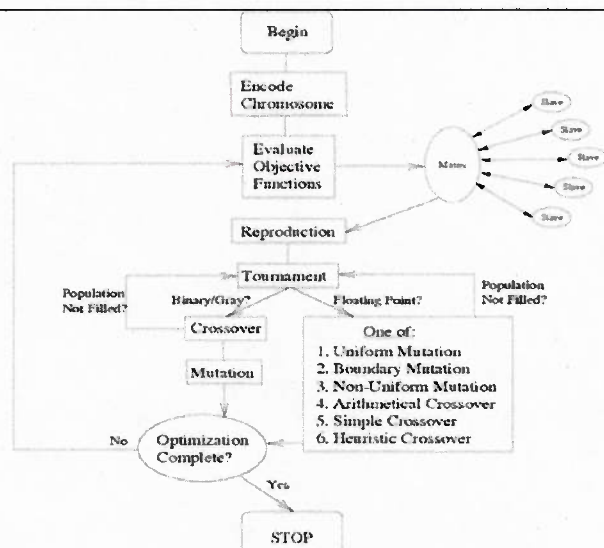


Figure 1.6. Parallelized genetic algorithm optimization methodology.

1.2 Previous Findings

Physical understanding and formulation to account for these complex interactions for hypersonic air-breathing vehicles are lacking at present, with the exception of a simple model suggested by Chavez and Schmidt [1.4]. With greatly simplified component forces and a dummy engine in their model, it can be concluded that the propulsive and aeroelastic interactions alone could indeed be destabilizing.

A brief survey of the current literature in the system consideration of the scramjet vehicle is presented in Table 1.1. It is disappointing to find that little of the current research has followed the pursuit of Chavez/Schmidt, who has mapped out a conceptual design/analysis path for future R&D efforts.

Although Chavez/Schmidt's work has been widely quoted in the literature [1.4], few followed to tackle the interactive AeroServoPropulsoElastic (ASPE) impact on the dynamic stability of the scramjet vehicles. Their work clearly indicated that such a type of analysis can be effectively handled through a "Conceptual-Design/Analysis" (CDA) approach. This is needed because the multi-disciplinary nature of ASPE would be otherwise far too complex as a system to handle. To do so, however, requires in depth physical understanding of the mechanism and interactions of all disciplines involved. This is in fact the physical-based model that is currently established by the ZONA Team.

Previous experience in the last decade also indicates that large discrepancies exist between measured data (wind-tunnel model) and flight data. This is so because the scaling law for different sizes of scramjet inlet/engine is simply non-existent at present. It is not clear in fact whether such scaling laws can ever be established. In the presence of vehicle aeroelasticity, the ASPE interactions of a scramjet vehicle would be vastly different between that derived from the measured and the flight test. For this reason, an analytical model for rapid assessment of the ASPE interaction as to the vehicle stability and control is badly needed.

The ZONA Team has created such a "Conceptual-Design/Analysis" (CDA) tool for precisely the purpose of rapid assessment of vehicle stability and control law implementation. In almost

every aspect, ZONA's CDA model has largely refined the features of Chavez/Schmidt's model. In particular, the essential improvements of the ZONA model over that of Chavez/Schmidt lies in the scramjet inlet/engine design feature and in the closed-loop control methodology, whereby both are lacking in Chavez/Schmidt's model. Details of our "Conceptual-Design/Analysis" (CDA) model will be described in what follows.

Table 1.1 Survey of Current Literature in the System Consideration of the Scramjet Vehicle

	Chavez et al [1.4]	*ZONA/UMD Team [1.5]*	*Mirmirani et al[1.6]*	*Bolender et al[1.7]*	*Baker et al[1.8]*	*Johnson et al[1.9]*
Configuration	2D Diamond	SEM Model of SED/ Waverider	X43A	2D Diamond	IHAT Geometry Models	Simple TSTO Wave-Rider
Conceptual Design Capability	Yes	Yes	-	-	Some	-
Aerodynamic Method for Design of Analysis	Shock Expansion (CD)	Hypersonic/ Euler & Viscous Aerodynamic Methods	CFD(A)	-	CFD	-
Inlet Design	-	Yes	-	-	-	-
Scramjet Combustion Model	Simple 1-D	2D Scramjet w/ Finite Rate Chemistry	Simple 1-D	Simple 1-D	-	-
Propulsion Dynamic Interaction	-	Yes	-	-	-	-
Flight Dynamics	Yes	Yes	-	(F) only	-	Yes
Elastic Vehicle/Aeroelastic Consideration/ASE	Yes	Yes	-	(F) only	-	Yes
Open/Close Loop Control & Methodology	-	Yes	-	-	-	-
Design Procedure: Formulation (F) & Solutions (S)	Yes	Yes	-	Mostly (F)	-	-
Thermal Protection System	No	Yes			Ablator	
Vehicle Optimization		Yes			Airframe	
Trajectory Optimization	No	Yes				

1.3 The ASTPE (Aero-Servo-Thermo-Propulso-Elasticity) Code

The ASTPE Software Architecture is shown in Figure 1.7.

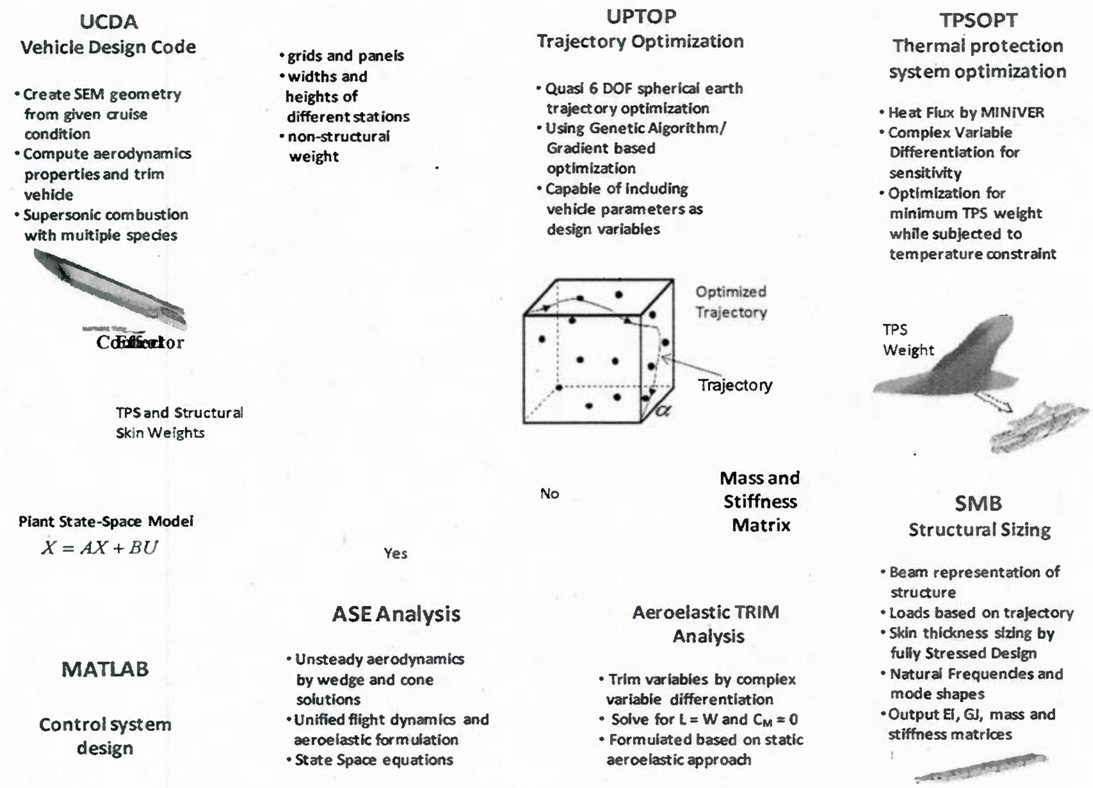


Figure 1.7 ASTPE Software Architecture

The ASTPE code consists of several modules as shown in Figure 1.7. The University of Colorado Design and Analysis code (UCDA) is used to design the vehicle and analyze it at some given trajectory. The University of Maryland Parallel Trajectory Optimization Program (UPTOP) optimizes the trajectory of the vehicle using the maximum range condition and the vehicle design. The Thermal Protection System Optimization (TPSOPT) code optimizes the TPS weight and sends the information to UCDA back so that the TPS weight can be updated for the vehicle. Using a fully stressed design method, Structural Modal Base (SMB) Module then optimizes the weight of the skin thickness subjected to the aerodynamic loads computed based on the optimized trajectory from UPTOP. SMB also generates the structural natural frequencies and their corresponding mode shapes that are needed to trim the vehicle with the structural flexibility effects in the next step considering an elastic vehicle using UCDA. Finally, once the

trim condition is computed, the aerodynamic stability derivatives at the trim condition are calculated which are the input of the Aero-Servo-Elasticity (ASE) module. The ASE module computes the longitudinal dynamics with structural flexibility effects and generates a state-space equation of the plant ready for flight control law design.

It should be noted that the procedure described above is for a single design cycle. The new trim solution and the change of the geometry of the vehicle due to the structural deformation as well as the additional weight due to the added thermal protection system and structural skin are used to update the design trim condition and the total vehicle weight, respectively, for the next design cycle. The design cycle will be repeated several times to arrive at a final design solution.

Chapter 2 University of Colorado Vehicle Design and Analysis (UCDA) Program

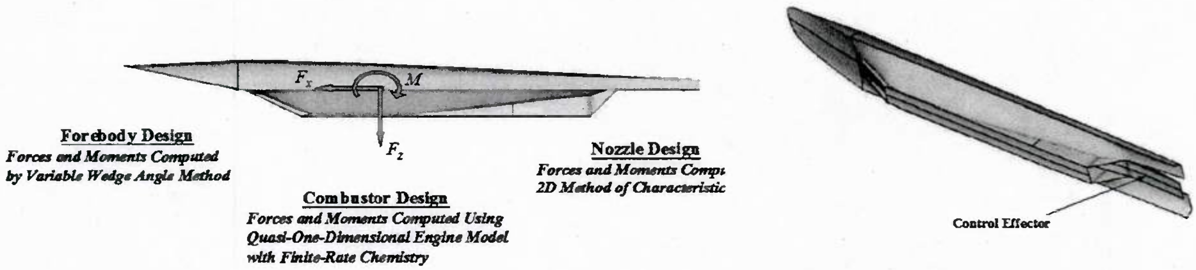
The University of Colorado Vehicle Design Code (UCDA) systematically creates a vehicle/combustor geometry based on inputs for forebody, inlet, combustor, nozzle, airframe, and control surface definitions. This works in either a one-off mode or interacts with the optimization software to develop a new design. Each major component has multiple methods of describing the geometry to increase/decrease the complexity and number of design variables required.

The current aerodynamic design and analysis methodology for both the waverider forebody and the vehicle aftbody are detailed below. There are a number of different ways to develop a waverider forebody; wedge generated flows, conically generated flow, blended flows, and osculating cone generated flows. The simplest of these is the analytical variable wedge angle method of Starkey and Lewis [2.1]; while the most flexible (and computationally expensive) is the osculating cone method of Sobiesky [2.2].

2.1 Waverider Design

The extreme sensitivities inherent in a missile-scale, hypersonic vehicle scramjet performance relative to the inlet conditions require detailed modeling of all associated components in order to capture the true physics [2.3]. When coupling this combustor sensitivity with aeroelastic effects the situation becomes much more complex.

In order to reduce the complexity of the models, the vehicle will utilize a two-dimensional keel-line flowpath, similar to that used in the Hyper-X program. As detailed in Figure 2.1, the main aerodynamic-propulsive components to be analyzed are: a waverider forebody, a scramjet combustor, and a simple two-dimensional nozzle.



(a) aerodynamic-propulsive formulation (b) control surface deflection

Figure 2.1 Generic single engine missile configuration

2.2 Variable Wedge-Angle Derived Waverider

The Variable Wedge-Angle waverider methodology was developed at the University of Maryland for reduced order, modeling of hypersonic waveriders [2.1]. The power in this method is in that the waverider forebody can be designed and analyzed analytically using only seven geometric design variables, as shown in Figure 2.2.

The computational fluid dynamics validation cases shown in Figure 2.3 show the power of the variable wedge angle method as a quick estimate of a waverider flowfield by producing an attached shock-wave at the design condition. Also shown is the minimal cross-flow (other than at the inflection point at the leading edge) thereby giving uniform flow into the airbreathing engine and demonstrating the applicability of strip theories to analyze the aftbody flow.

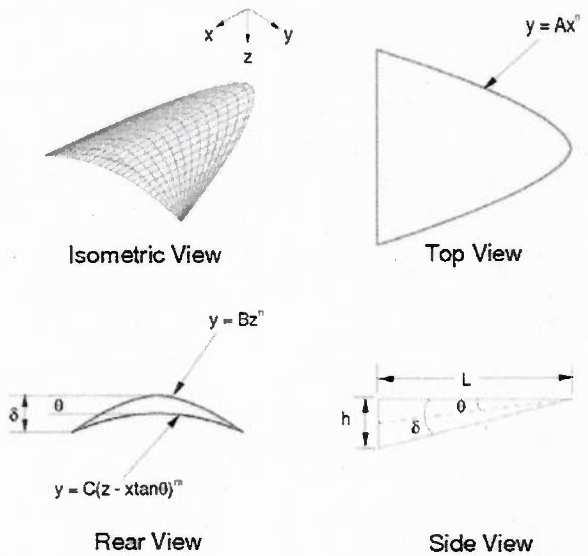
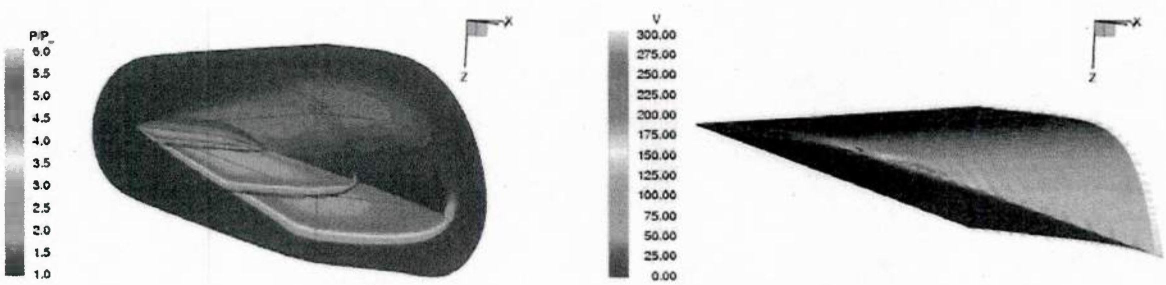


Figure 2.2 Variable wedge-angle waverider forebody



(a) pressure contours **(b) cross-flow velocity vectors**

Figure 2.3 CFD validation of VWA methodology

For a Mach 8, zero degree angle-of-attack design point of the forebody, off-design performance at various Mach numbers and angles of attack is shown in Figure 2.4. The only discrepancy is near the zero-lift point where the absolute difference is small, but the % difference is large. Therefore, the variable wedge angle methodology is shown to be comparable to the osculating cone method and CFD analysis for changes in Mach number and angle of attack.

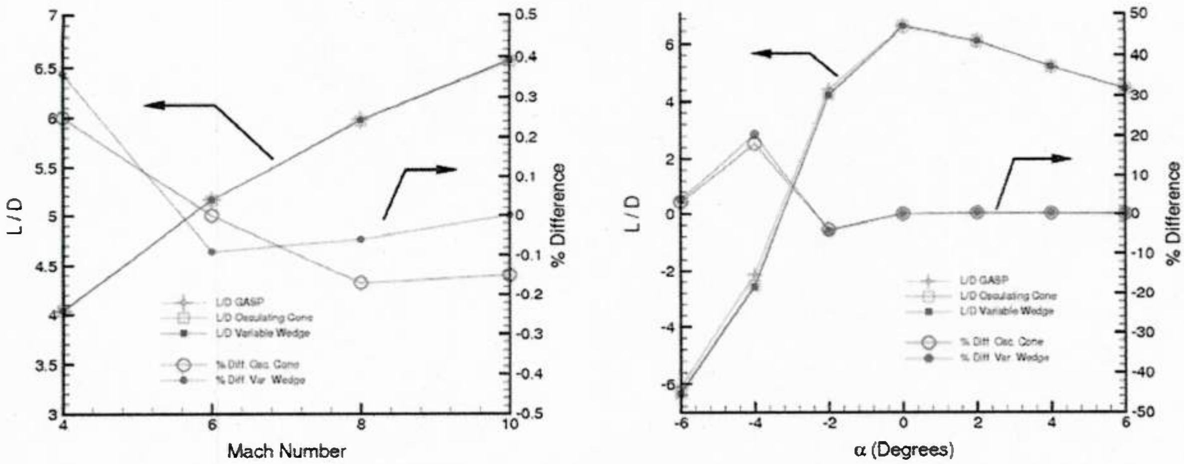
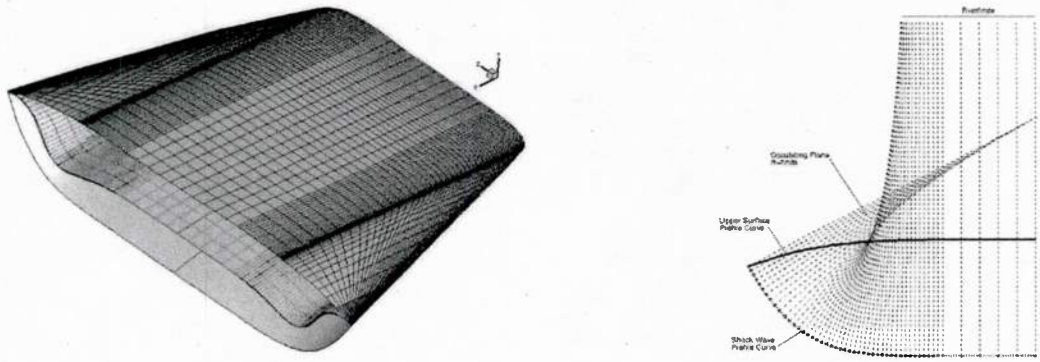


Figure 2.4 *L/D* ratio and % difference for CFD, osculating cone, and variable wedge angle analyses of a Mach 8 forebody

2.3 Osculating Cone Waverider

True waveriders are generated using an inverse design method; one where the desired flowfield is chosen and the vehicle that generates that flowfield is produced. One method of waverider generation, first conceived of by Sobieczky et al. [2.2], where multiple slices of a conical flowfield are placed side-by-side to build up the desired flowpath, is referred to as the method of osculating cones [2.4], as shown in Figure 2.5. The keel-line flowfield can be generated in this manner to provide uniform flow to a two-dimensional combustor while providing the high lift-to-drag ratio (*L/D*) at a high lift coefficient (C_L) that waveriders are well known for. In addition to the compression provided by the waverider, the inlet system also utilizes a number of planar compression ramps which satisfy an on-design shock-on-lip constraint.



(a) (b)

Figure 2.5 Osculating cone waverider with a) shock flowfield at combustor inlet plane and b) inlet plane compression surface generation [2.5]

2.4 Modified Shock-Expansion Method Formulation

Another innovation used in this stage of the vehicle analysis (for fast optimization studies) is a modified shock-expansion method. Shock-expansion theory is inaccurate for this application because it determines the flowfield using single Prandtl-Meyer expansions (hypersonic slender body theory) assuming two-dimensional streamlines. Due to the highly curved nature of these missile airframes, the shock-expansion method results in an over-prediction in peak surface pressure by as much as 50%. The modified method uses a combination of the oblique shock relations and Taylor-Maccoll cone flow equations to solve the local flow properties (for compression) while marching down a 'two-dimensional' streamline. As with the shock-expansion theory, the local flow conditions and the relative inclination angle at a point are used to calculate the properties at the next point. The blending of the properties predicted by the oblique shock and Taylor-Maccoll methods is based on the local radius of curvature in the spanwise direction. This attempts to predict the pressure relieving effects a three-dimensional body has on a two-dimensional streamline approximation to local flow conditions. Expansion regions are calculated using traditional shock-expansion theory.

A similar method using a blend of Tangent Wedge and Tangent Cone approximations to off-design flowfield predictions for osculating cone generated waveriders was developed by Grantz [2.6]. Grantz's method was not applicable to this study since it requires a known generating

body with a known flowfield (i.e., streamline locations), such as the method of osculating cones, to determine the surface properties of the body.

Continuing with the assumption of two-dimensional flow, the surface properties at a point are solved using the known properties at the previous point and the local body angle, relative to that point. For oblique shock theory, the wedge angle used to determine the new properties, and for cone flow the cone half angle is used. For a known surface point, with initial properties, P_1, T_1, and M_1, the relative surface angle is used to determine the new properties. Assuming only wedge flow the results are given by P_{2w}, T_{2w}, and M_{2w}, with completely conical flow given by P_{2c}, T_{2c}, and M_{2c}.

The local radius of curvature R is determined in the spanwise plane by:

$$R = \frac{\left[1+(y')^2\right]^{3/2}}{|y''|} \tag{2.1}$$

The actual surface properties for compression surfaces are found by linear interpolation in the form $\lambda = R\lambda_w + (1-R)\lambda_c$ where w values are calculated from oblique-shock theory, c values are determined from solution to the Taylor-Maccoll equations, and λ indicates each of P, T, and M at a given location. Results using this methodology have been validated using Euler computational fluid dynamics (CFD) calculations as shown in Figure 2.6.

Figure 2.6(a) shows the missile airframe neglecting the engine flowpath, since Figure 2.6(b) demonstrated the two-dimensional nature of the keel-line flow. The top half of each vehicle pictured in Figure 2.6 is the Euler CFD solution while the bottom half is the modified shock-expansion method. As can be seen, there are only minor differences in the solutions, but the solution run-times are many orders of magnitude apart since the analytical blending function takes only a fraction of a second to compute. Figure 2.6(b) is a close-up view of the peak pressure location.

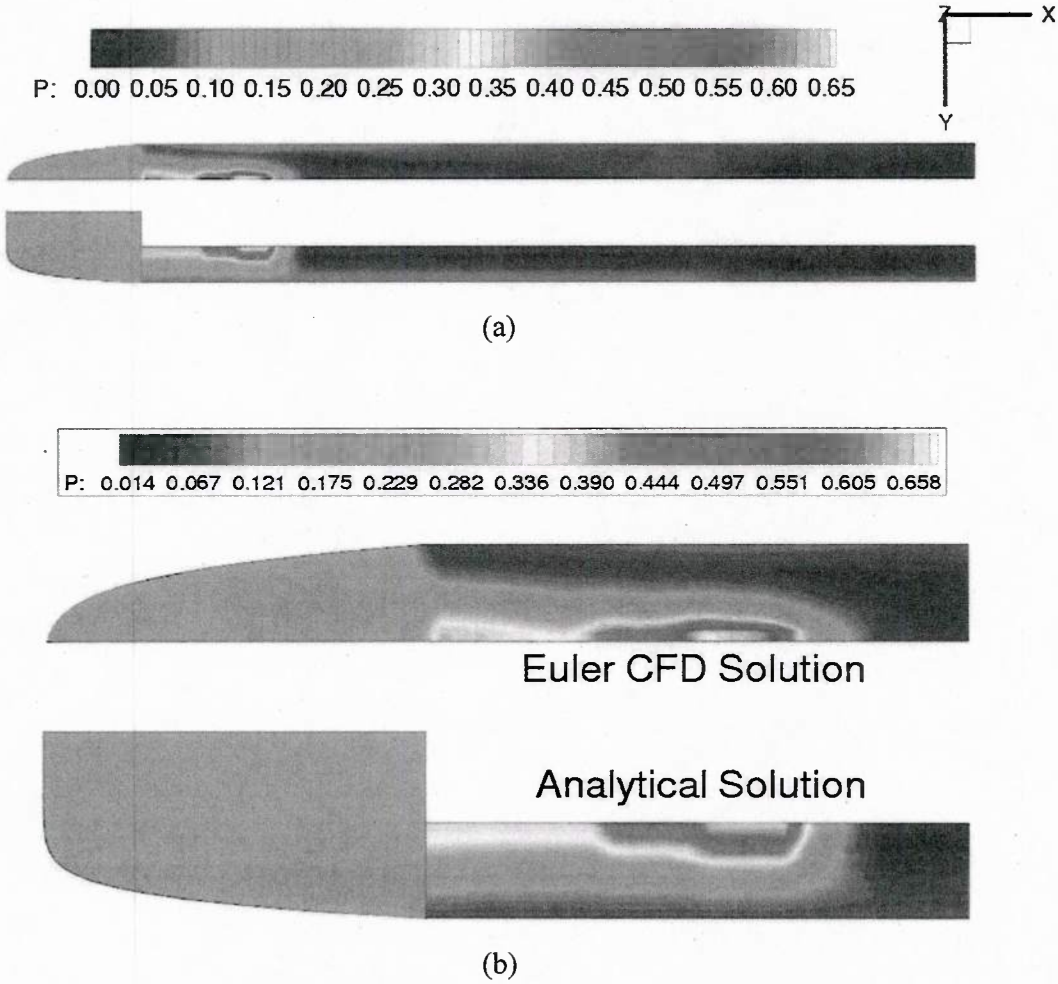


Figure 2.6 Validation of modified shock-expansion methodology for three-dimensional pressure relieving effects along two-dimensional streamlines

2.5 Scramjet Combustor

The scramjet combustor is generated in a two-dimensional manner with an isolator section followed by one or more expanding sections, as shown in Figure 2.7(a). The fuel (and pilot agent if desired) can be injected through any number of ports in any position throughout the combustor. Figure 2.7(b) shows a mixing profile and burning efficiency are then applied to determine the effects of the inlet conditions, fuel, and geometry on the combustion using finite-rate chemistry computations [2.7].

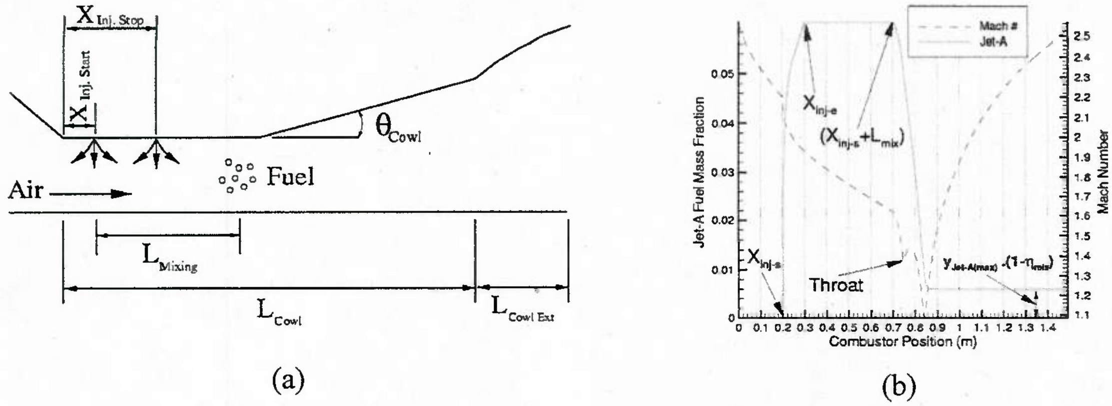


Figure 2.7 (a) Scramjet combustor model, (b) sample Jet-A fuel Mass fraction and mach number as a function of combustor position

The elegance of this scramjet model is in the formulation of the finite-rate chemistry inclusion in the quasi-one-dimensional equations of fluid motion. Using this model the design sensitivities of various fuel types, chemistry mechanisms, injector locations and angles, viscous effects, and wall heat transfer can be determined in a computationally efficient manner. The inclusion of chemical kinetics allows for a prediction of fuel ignition, a finite-rate process that inherently cannot be predicted using equilibrium methods. Chemistry also allows for off-design calculations to determine what conditions are needed for the fuel to burn, and what conditions will cause the combustor to choke. These prediction abilities are crucial in flowfield regimes where the limits of the scramjet concept are seen (i.e., hydrocarbon missile scramjets, ram/scram transition, etc.).

The series of ordinary differential equations that model the governing equations of motion are shown below. Along with a user specified cross-sectional area profile, mass and reaction mixing profile, viscous model, and a reaction mechanism, the ordinary differential equations are integrated to solve for the combustor flowfield.

Equations for continuity, momentum, state, mixture molecular weight, species conservation, and energy are shown below, respectively.

$$\frac{1}{\dot{m}}\frac{d\dot{m}}{dx}=\frac{1}{\rho}\frac{d\rho}{dx}+\frac{1}{U}\frac{dU}{dx}+\frac{1}{A}\frac{dA}{dx} \tag{2.2}$$

$$\frac{1}{p}\frac{dp}{dx}+\frac{\gamma M^2}{2U^2}\frac{dU^2}{dx}+\frac{2\gamma M^2 C_f}{D}+\frac{\gamma M^2(1-\varepsilon)}{\dot{m}}\frac{d\dot{m}}{dx}=0 \tag{2.3}$$

$$\frac{1}{p}\frac{dp}{dx}=\frac{1}{\rho}\frac{d\rho}{dx}+\frac{1}{T}\frac{dT}{dx}-\frac{1}{\overline{MW}}\frac{d\overline{MW}}{dx} \tag{2.4}$$

$$\frac{d\overline{MW}}{dx}=-\overline{MW}^2\left(\sum_i\frac{1}{MW_i}\frac{dY_i}{dx}\right) \tag{2.5}$$

$$\frac{dY_i}{dx}=\frac{\dot{\omega}_{i,mix}MW_i}{\rho U}+\frac{1}{\dot{m}}\frac{d\dot{m}_{i,added}}{dx}-\frac{Y_i}{\dot{m}}\frac{d\dot{m}}{dx}, \tag{2.6}$$

$$\frac{dT}{dx}=\frac{1}{\hat{c}_p}\left[-\sum_i h_i\frac{dY_i}{dx}+\frac{1}{\dot{m}}\sum_i\left(h_i\frac{d\dot{m}_i}{dx}\right)_{added}-\frac{2C_f c_p\left(T_{aw}-T_w\right)}{Pr^{2/3}DA}-\frac{h_o}{\dot{m}}\frac{d\dot{m}}{dx}-U\frac{dU}{dx}\right] \tag{2.7}$$

where

$$\hat{c}_p\equiv\tilde{c}_p-\frac{1}{\dot{m}}\left\{\sum_i\left[\dot{m}_i\left(c_{pi}+\tilde{c}_{pi}T\right)\right]_{added}\right\} \tag{2.8}$$

and

$$\tilde{c}_p\equiv c_p+\sum_i T\,\tilde{c}_{pi}\,Y_i \tag{2.9}$$

$$\tilde{c}_{pi}\equiv\frac{R_u}{MW_i}\left(a_{2i}+2a_{3i}T+3a_{4i}T^2+4a_{5i}T^3\right) \tag{2.10}$$

These equations constitute a stiff set of ordinary differential equations (ODE) due to the chemical production terms from combustion. Solution of these equations a stiff ODE solver which can account for differing time scales. A code named VODPK [2.8], developed by Lawrence Livermore National Lab, was used to accomplish this task. VODPK uses a backward differentiation formula to integrate the set of stiff ODEs. Values for the individual chemical species molecular weight, specific heat, heat of formation, and reaction rates are obtained by CHEMKIN-II [2.9] for a user-supplied reaction mechanism.

For this study only Jet-A fuel was investigated, although any fuel could be used. The Jet-A reaction mechanism used in this study is a subset of the full reaction mechanism from Kundu et. al [2.10]. The reaction mechanism consists of 17 species and 14 reactions and was chosen because it has been validated by Chang and Lewis [2.11]. The ambient air composition is assumed to be 78% nitrogen, 21% oxygen and 1% argon by volume.

Solving the equations for conservation of mass, momentum, energy, and the equation of state for the derivative in velocity yields:

$$\frac{dU}{dx} = \frac{1}{\alpha}\left\{ -\frac{1}{A}\frac{dA}{dx} + \frac{1+\gamma M^2(1-\varepsilon)-\left(h_o/\hat{h}\right)}{\dot{m}}\frac{d\dot{m}}{dx} + \frac{1}{\hat{h}}\left[-\sum_i h_i \frac{dY_i}{dx} + \frac{1}{\dot{m}}\sum_i \left(h_i \frac{d\dot{m}_i}{dx}\right)_{added} \right] \right.$$

$$\left. -\frac{1}{MW}\frac{dMW}{dx} + \left[\gamma M^2 - \frac{c_p\left(T_{aw}-T_w\right)}{\hat{h}\,Pr^{2/3}A} \right]\frac{2C_f}{D} \right\} \qquad (2.11)$$

where

$$\alpha \equiv \frac{1}{U}\left(1-\gamma M^2 + \frac{U^2}{\hat{h}} \right) \qquad (2.12)$$

and

$$\hat{h} \equiv \hat{c}_p T \tag{2.13}$$

Each term in the dU/dx derivative can be calculated, or is a prescribed quantity. The first term is the cross-sectional area profile dA/dx which is assumed to be prescribed by the user. The second term is the mass flow addition term of $d\dot{m}/dx$ and represents the mass mixing profile prescribed by the user. The quantity $\hat{h}$ can be calculated using CHEMKIN-II. The solution of the change in mixture molecular weight $d\overline{MW}/dx$ is found by first solving the species conservation equation. Given the mixing profile and chemical information from CHEMKIN-II, the conservation of species is a known quantity which may then be substituted into the mixture molecular weight equation to solve for the change in mixture molecular weight. The friction terms involving the friction coefficient are all known quantities or may be calculated using CHEMKIN-II. The remaining terms in dU/dx are known quantities, quantities that have already been calculated, or quantities that may be calculated using CHEMKIN-II. Thus, the velocity derivative derived in dU/dx is a known quantity at a particular x-location in the combustor.

With knowledge of the velocity derivative, the density derivative may be found from the continuity equation. The pressure derivative may be calculated from the momentum equation. The temperature derivative is then found from the equation of state. The derivatives of all the variables are then integrated using VODPK to find the flow solution. The full engine flowfield may be calculated in a fraction of a second on a standard take-off computer. Thus, this method allows for rapid design of full vehicle concepts that include a detailed engine flowfield.

The mixing model used is that of Rogers [2.12], tabulated by Henry and Anderson [2.13]

$$\dot{m}_r = \dot{m}_f \frac{a\bar{x}^b \, exp(c\bar{x})}{d\bar{x} + f} \tag{2.14}$$

$$\bar{x} \equiv \frac{x}{L_{inj}} \tag{2.15}$$

where L_{inj} is the length between the start and end of the injection and the curve-fit constants are $a = 1.1703$, $b = 0.62925$, $c = 0.42632$, $d = 1.4615$, and $f = 0.32655$.

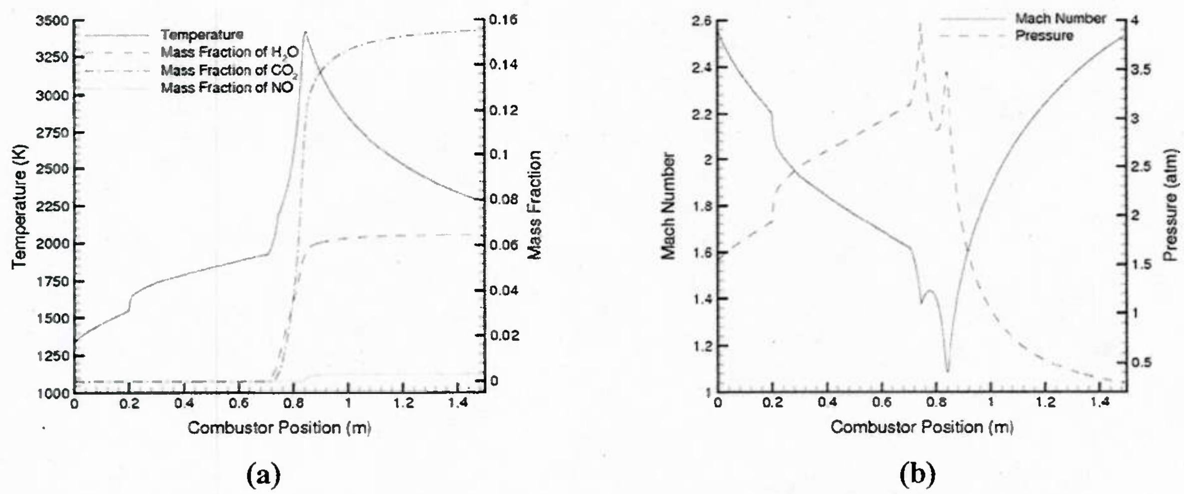


Figure 2.8 Sample scramjet performance with (a) Mach number and pressure distribution, and (b) temperature and species mass fraction distributions

The importance of using finite-rate chemistry to accurately predict the fuel ignition point and the effects of the combustor geometry and the energy release can be seen in Figure 2.7. The Mach number and pressure distribution for a sample combustor are shown in Figure 2.8 (a), while the temperature and species mass fractions (to show fuel burning efficiency) are shown in Figure 2.8 (b). In this instance, the combustor is 1.5 meters long with the constant area portion of 0.75 meters long and the expansion section the following 0.75 meters. The fuel ignition occurs just before the expansion area and the interplay between the combustor geometry and heat release are

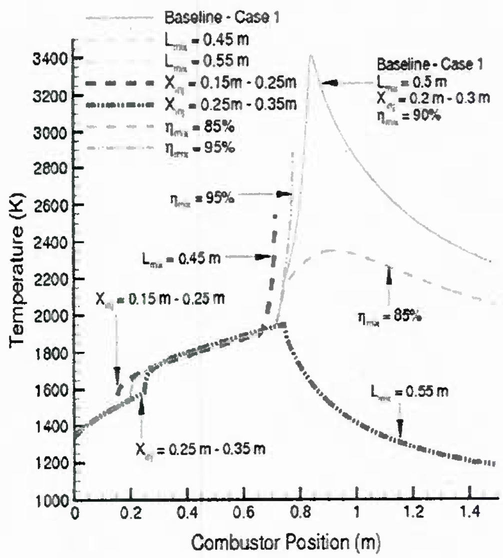


Figure 2.9 Combustor temperature contours for off-baseline conditions

evident. The sensitivity of the combustor performance relative to the ignition point is detailed in Figure 2.9. By varying a few of the combustor design conditions slightly off of baseline, the performance degraded very quickly with most of the variations resulting in thermally choked flow. Only two conditions did not result in a choked flow state: 1) lowering the mixing efficiency from 90% to 85% (lowering the heat release), and 2) increasing the mixing length from 0.5 meters to 0.55 meters (delaying ignition until after the mechanical throat). The only off-baseline condition which retained a moderate amount of performance was the lower mixing efficiency case, otherwise the engine would unstart.

Although some of the design conditions were altered to determine the sensitivity, similar results occur for off-design flight performance is especially once the angle-of-attack increases a few degrees or the Mach number increases past the design point (both causing increased inlet pressure). Alleviating these concerns can only be done through bleeds, spillage, bypass, or geometry variations [2.3] and [2.14].

2.6 Nozzle

Following the combustor are the internal and external nozzle sections, which are calculated using the frozen, non-rotational, two-dimensional method of characteristics, as shown in Figure 2.10. Since part of the nozzle is utilized as a control surface in this configuration the combustor flowfield directly affects the vehicle trim state.

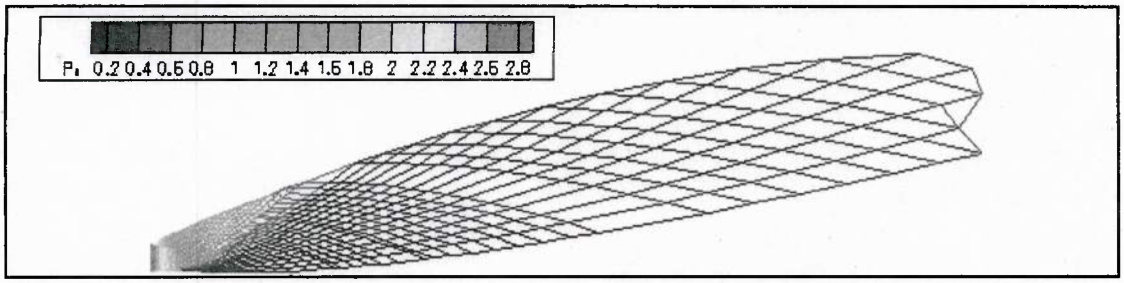


Figure 2.10 Sample method of characteristics nozzle design showing pressure contours

Using the design fuel equivalence ratio as the combustor state, the control surface effectiveness can be determined, as shown in Figure 2.11. The trim state in this instance is at a slightly downward control surface deflection, as shown in Figure 2.12.

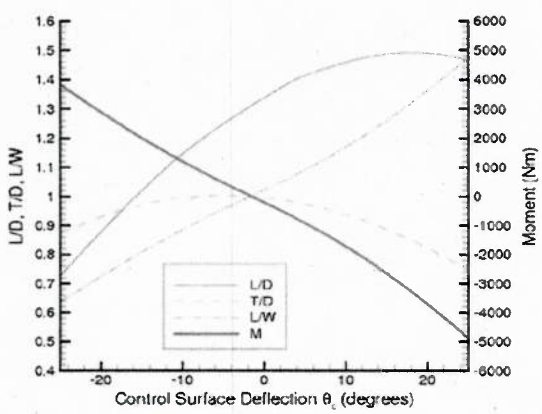


Figure 2.11 Control surface effectiveness at the design fuel equivalence ratio

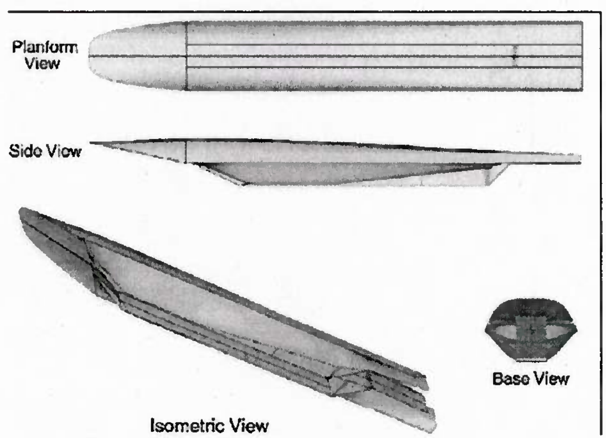


Figure 2.12 Baseline vehicle configuration

2.7 Superformula of the Superellipse

The superformula of the superellipse [2.15] is one option for generating the top surfaces of both the forebody and afterbody of the vehicle models. The typical superellipse formula can transform a parallelogram into an ellipse with the Cartesian equation

$$\left|\frac{x}{a_1}\right|^{v} + \left|\frac{y}{b_1}\right|^{v} = 1$$

whereas the superformula of the superellipse can transform a polygon into an ellipse or a concave polygon using the equation by determining a radial displacement r along each angle φ.

$$r(\phi) = \left[\left|\frac{\cos\left(\frac{1}{4}m\phi\right)}{a_1}\right|^{n_2} + \left|\frac{\sin\left(\frac{1}{4}m\phi\right)}{b_1}\right|^{n_3} \right]^{-1/n_1}$$

In this equation, the exponents n_1, n_2, and n_3 alter the curvatures while the variables a_1 and b_1 control the axis lengths. Finally, the variable m controls the number of sides or lobes. Examples of certain parameter settings are given in Fig. 2.13 with a more thorough listing in Fig 2.14 (with many non-ideal geometries).

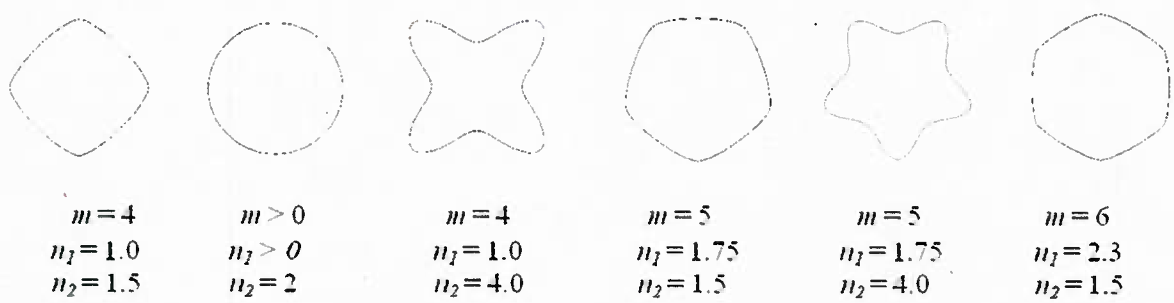


Figure 2.13 Example geometries created using the superformula of the superellipse.

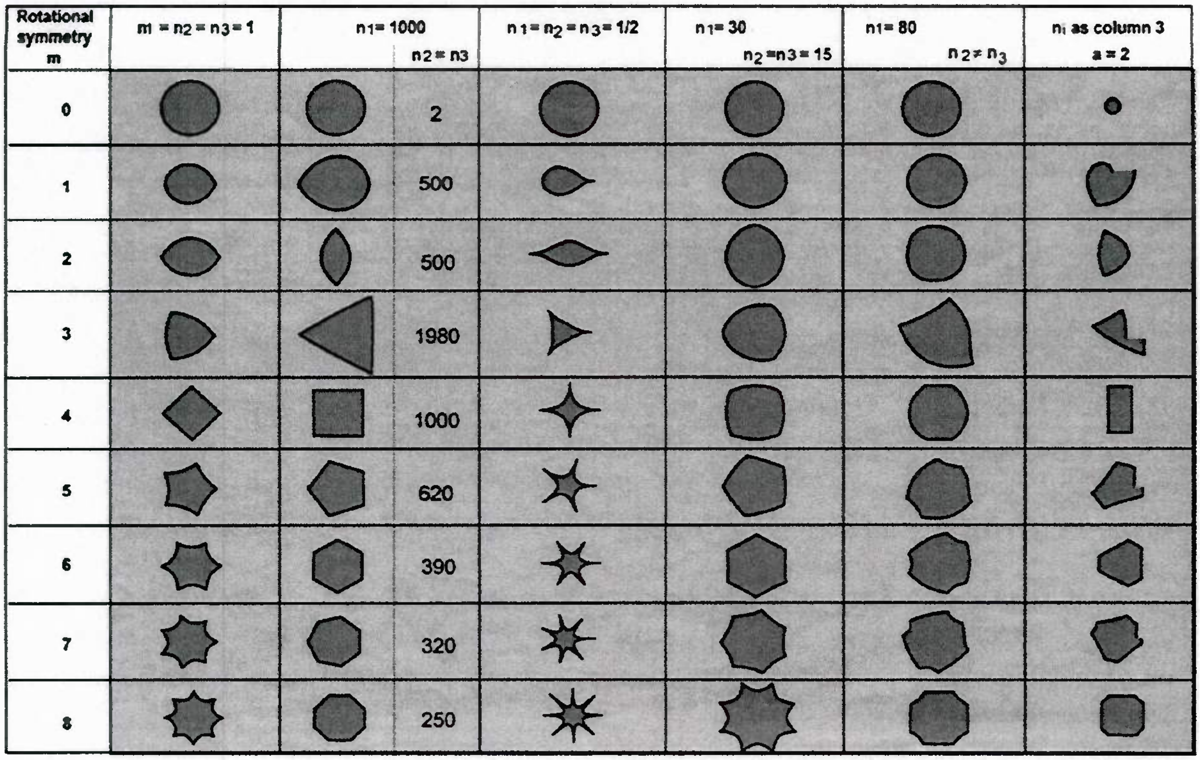


Figure 2.14 Example geometries created using the superformula of the superellipse.

Chapter 3 University of Maryland Parallel Optimization Program (UPTOP) Program

3.1 Introduction

The University of Maryland Parallel Trajectory Optimization Program (UPTOP) is a generalized atmospheric and near-earth orbit trajectory optimization program written in Fortran 95. UPTOP combines a Differential Evolutionary Scheme (DES) with a gradient-based optimizer to provide optimal results without requiring a feasible initial condition. UPTOP is capable of optimizing multi-stage trajectories where the vehicle may have multiple engines and fuel tanks. Input to the code consists of two simple input decks and interpolation tables to define the aerodynamic characteristics and engine performance. The current capabilities of the code also allow for elementary sizing studies and provide the user with the ability to optimize vehicle parameters such as fuel weight and reference areas. Additionally, the user can define a set of relationships between the vehicle parameters so that the effects of a change in one vehicle parameter will be accurately reflected in the vehicle's performance. Users can also define new variables to be tracked or used throughout the trajectory optimization. UPTOP is a modular code written with expansion in mind, and provides a solid base for delving into guidance and control issues.

UPTOP calculates up to 200 parameters, providing information on vehicle states and orientations, atmospheric states, orbital elements, etc. User-defined variables can also be integrated into the code, allowing for easy addition of heating or weight analysis, for example. Additionally, simple tracking operators, such as average, max/min, or standard deviation, can be applied to all variables.

User inputs consist of initial conditions (i.e., initial altitude, velocity, etc.) and variable profile definitions (i.e. angle of attack or throttle profiles, as a function of time). Most variable profiles can be specified using one of four methods:

<u>Constant definition</u> – user defines a constant value for the variable.

<u>Curve Fit</u> - user defines the value of the function at user-specified points in time, and UPTOP fits a series of piecewise curves to the data, using a function of a user-specified order. Dependencies between the individual variables in the table can also be established (for example, point 4 can occur 20 seconds after point 3).

<u>Look-up Table</u> - user includes a look-up table that provides the variable value based on up to 10 independent variables. UPTOP then uses linear interpolation to calculate the variable value.

<u>Event Driven</u> - user specifies events in terms of independent variables that, when triggered, result in changes to the dependent variable.

Most trajectory input values and vehicle parameters can be included in the optimization process, unless they are specified as a look-up table. Further, relationships between the vehicle parameters can easily be built in order to perform elementary sizing studies. More information is included in the UPTOP Usage Manual

3.2 Simulation

UPTOP uses a 4th-order Runge Kutta scheme and information regarding the vehicle's aerodynamic and engine performance to propagate the vehicle position, velocity, and orientation throughout time. The simulation aspects of UPTOP are discussed in more detail below.

3.2.1 Coordinate Systems

UPTOP maintains four coordinate systems for tracking the vehicle position and orientation.

- Earth-Centered Inertial (ECI) - positioned at planet center, with the 1-axis pointing through the northern pole, the 2-axis aligned with 0 deg longitude at time = 0, and the 3-axis at 90 deg longi6tude at time = 0. This frame does not rotate with the earth, however the earth rotates around the ECI 1-axis.

- North-East-Down - positioned at A/C c.g. and serves as local horizon. The 1-axis always points North and the 3-axis always points to the center of the earth, with the 2-axis pointing East. The relation between the ECI and NED frames is shown in Fig. 3.1.

- Velocity frame (VEL) – positioned at A/C c.g., with the 1-axis pointing in the opposite direction as the freestream velocity vector. VEL begins with NED frame, rotates around 3-axis by heading angle, then about 2-axis by flight path angle.

- Aircraft Body Coordinates - positioned at A/C c.g., with the 1-axis aligned with A/C nose, the 2-axis along the A/C right wing, and the 3-axis pointing down (with respect to pilot in level flight). The relation between the VEL and ABC frames is shown in Fig. 3.2.

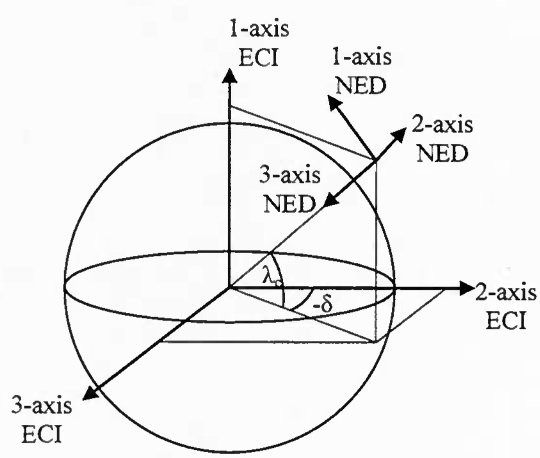
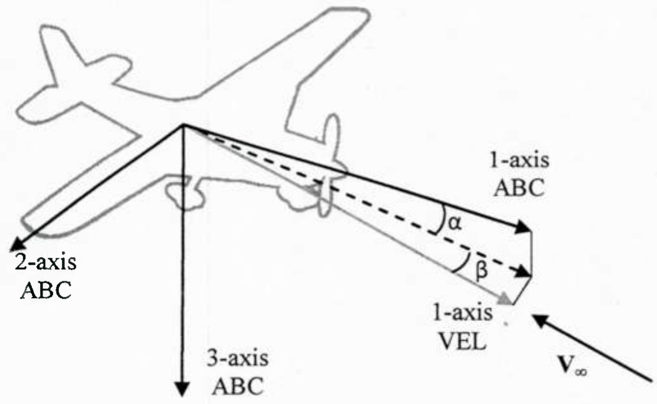


Figure 3.1 ECI and NED reference frames



UPTOP uses direction cosine matrices to change vectors from one reference frame to another. For more information regarding reference frames, see Refs. [3.7] and [3.10].

Figure 3.2 ABC and VEL reference frames

3.2.2 Planet Modeling

UPTOP assumes a rotating, oblate spheroid earth with a flattening parameter of 0.0033528. In UPTOP, the vehicle's geocentric latitude, geodetic latitude and longitude (both over an inertial and rotating planet) are tracked.

The gravity vector, **g**, is defined in UPTOP as:

$$\mathbf{g} = -\frac{\mathrm{GM}}{\|\mathbf{p}\|^3}\begin{bmatrix}\overline{p}_x \\ \overline{p}_y \\ \overline{p}_z\end{bmatrix}$$

where **p** is the position of the aircraft in the ECI frame and GM is the Earth-mass gravitational constant (3.9860×10^{14} m^3/s^2). The values of $\overline{p}$ are used to account for the oblateness of the earth by incorporating the J_2 gravitational harmonic constant, such that:

$$\overline{p}_x = p_x\left[1 + 1.5J_2\left(\frac{r_e}{\|\mathbf{p}\|}\right)^2\left(3 - 5\sin^2\lambda\right)\right]$$

$$\overline{p}_y = p_y\left[1 + 1.5J_2\left(\frac{r_e}{\|\mathbf{p}\|}\right)^2\left(1 - 5\sin^2\lambda\right)\right]$$

$$\overline{p}_z = p_z\left[1 + 1.5J_2\left(\frac{r_e}{\|\mathbf{p}\|}\right)^2\left(1 - 5\sin^2\lambda\right)\right]$$

where $J_2 = 1.08263\times10^{-3}$, r_e is the equatorial radius of the Earth, and λ is the geocentric latitude.

UPTOP incorporates two atmosphere models, the 1976 US Standard Atmosphere [3.1] and NRLMSISE-00 [3.5]. The 1976 US Standard Atmosphere is used by default for altitudes below 88km. Above 88km, UPTOP uses NRLMSISE-00 model. The user may also select NRLMSISE-00 for all altitudes. Winds are not modeled in UPTOP.

3.2.3 Vehicle Dynamics

The equations of motion for rigid-body flight are given by:

$$\frac{d\mathbf{p}}{dt} = \mathbf{V} \tag{3-1}$$

$$\frac{d\mathbf{V}}{dt} = B\frac{1}{m}\mathbf{F}_b + \mathbf{g} \tag{3-2}$$

$$\frac{dm}{dt} = -\left(\frac{dm}{dt}\right)_f \tag{3-3}$$

$$\frac{d\mathbf{q}}{dt} = -\frac{1}{2}\Omega_q\mathbf{q} \tag{3-4}$$

Eqs. (3-1) and (3-2) describe the changes in the inertial position, **p**, and velocity, **V**, vectors as a function of the vehicle mass, *m*, gravity, **g**, and external force vector as specified in the ABC frame, $\mathbf{F}_b$. The direction cosine matrix, *B*, is used to rotate the external forces from the ABC frame to the ECI frame. Eq. (3-3) describes the vehicle mass change as a function of fuel mass consumption. Finally, Eq. (3-4) provides the update for the quaternion vector, **q**, used to track vehicle orientation.

Missing from this set of equations is the rate of change of the angular rate values as a function of vehicle mass moment of inertia and external torques. UPTOP is a trimmed-vehicle code, and does not consider the effects of torque on the vehicle. Instead, the user specifies the vehicle orientation profile as a function of time. This defines the angular rates, and allows the body-axis angular rate vector in the inertial frame, $\omega_{B/I} = [P, Q, R]$, to be calculated. Then,

$$\Omega_q = \begin{bmatrix} 0 & P & Q & R \\ -P & 0 & -R & Q \\ -Q & R & 0 & -P \\ -R & -Q & P & 0 \end{bmatrix}$$

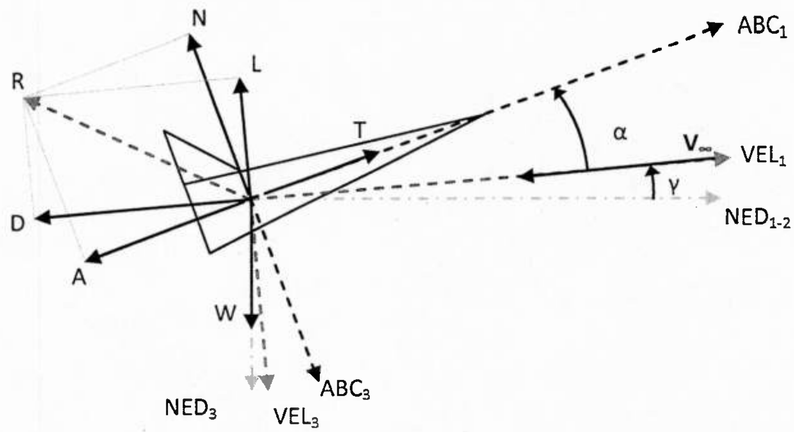


Figure 3.3 Vehicle external forces

The vehicle angular rotation rates are discussed further in Sec. 3.2.5. Additional details regarding rigid body dynamics and reference frames can be found in standard vehicle dynamics texts, including Refs. [3.7] and [3.10].

UPTOP uses a 4th order Runge-Kutta routine to propagate the equations of motion while minimizing numerical inaccuracies. The user must specify a time-step and a maximum allowed time to aid in memory allocation.

3.2.4 Vehicle Forces

UPTOP accounts for the effects of aerodynamic and thrust forces on the vehicle's path, however, UPTOP does not account for vehicle moments (see Sec. 3.2.5). The aerodynamic forces can be specified relative to the velocity vector (lift and drag) or relative to the vehicle axes (normal and axial). Alternatively, the force coefficients can also be defined, such that

$$X = C_x qS$$

where X is replaced with the appropriate parameter, q is the dynamic pressure, and S is the corresponding reference area (planform area for aerodynamic values, engine exit area for thrust).

Figure 3.3 shows a graphic representation of the forces on the vehicle. Lift and drag ('L' and 'D') lay on the axes of the velocity vector (VEL) frame, whereas the normal and axial forces ('N' and 'A') lay on the aircraft body fixed (ABC) axes. The resultant of the aerodynamic forces, R, is included in the figure for the convenience of the reader when relating the forces in the two frames. The vehicle weight always points towards the center of the earth (along the NED 3-axis), and the thrust vector, T, always points along the 1-axis of the ABC frame. Figure 3.3 also shows that the angle γ, at which the velocity vector meets the NED 1-2 plane (i.e., the local horizon) defines the flight-path angle.

3.2.5 Vehicle Position and Orientation Calculation

UPTOP does not consider vehicle aerodynamic moments or the effects of external torques from control surfaces or thrust vectoring when calculating the vehicle's trajectory. Instead, the user specifies the vehicle orientation as a function of time. Usually, this is done by defining the vehicle aeroballistic angles (angle of attack, bank, and yaw angle) or the vehicle Euler angles or angular rates relative to the NED frame.

With the vehicle orientation, known at time t_i, UPTOP then calculates the aerodynamic and thrust forces applied to the vehicle and uses the information provided by the user (these data are assumed to apply to a trimmed vehicle). The external forces, along with the current position and velocity, are used to determine the vehicle position and velocity at t_{i+1} using Eqs. (3-1) and (3-2).

Depending on the orientation input mode, Eq. (3-4) may require closer attention. The quaternion update is dependent on the angular rotation rate of the ABC frame relative to the ECI frame, $\{\omega_B\}_I$. If the user specifies the vehicle orientation using inertial angles, P, Q, and R are simply the derivatives of those angles with respect to time. However, typically the user will wish to specify the vehicle orientation in more familiar terms, such as pitch relative to the local horizon, or angle of attack. For the former, the rotation of the ABC frame relative to the NED frame is defined. In that case, the angular rate of the ABC frame relative to the NED frame must be added to the angular rate of the NED frame with respect to the ECI frame (since the local horizon rotates as the vehicle moves around the spherical earth), such that $\{\omega_B\}_I = \{\omega_B\}_N + \{\omega_N\}_I$.

If the user specifies the vehicle orientation in terms of the aeroballistic angles, the process to find $\{\omega_B\}_I$ requires an iterative scheme. The aeroballistic angles define the ABC frame relative to the VEL frame, so the body-axis angular rates are now $\{\omega_B\}_I = \{\omega_B\}_V + \{\omega_V\}_N + \{\omega_N\}_I$. However, the rotation of the VEL frame with respect to the NED frame is not known beforehand, and must be iterated upon by guessing and refining values for the change in flight path angle and heading with respect to time, until Eqs. (3-1) and (3-2) are consistent, and the desired values of angle of attack and sideslip angle have been acquired at the following time step.

3.2.6 Stagnation Point Heating

UPTOP employs a simple heating model, due to Tauber, to estimate the vehicle stagnation point heating rate. The heating equation is a function of the vehicle nose radius and wall temperature. The user may specify a fixed wall temperature, or allow UPTOP to estimate the equilibrium wall temperature. See Ref. [3-8] for more details.

3.3 Optimization Overview

Although random-based evolutionary algorithms (EA's) are generally praised for their ability to find global optima, their efficiency as the objective function approaches the optimum typically

decreases significantly. In the near-optimal space, the classical gradient-based optimization techniques excel. This leads to the concept of hybrid optimization techniques that combine the strengths of the two disciplines.

Madavan [3.3, 3.4] provides an overview of efforts to hybridize differential evolutionary schemes, and also shows increased performance by combining Differential Evolutionary Scheme (DES) with dynamic hill climb (DHC). The current work uses the Design Optimization Tool (DOT) package [3.9]; more specifically calling the sequential quadratic programming (SQP) routine. SQP is an efficient constrained optimization technique that minimizes a quadratic approximation to the objective function subject to linearized constraints. Details of the method are available throughout literature and included in the DOT manual [3.9].

Previous work using UPTOP has shown that coupling SQP with DES provides an effective method of optimization that is more powerful than either method alone. The results obtained from the hybrid method shows a consistency and reliability that is greatly desired in optimization work, since it may reduce the amount of tuning required when examining a new problem.

3.3.1 Differential Evolutionary Scheme Overview

DES shares a framework with most evolutionary algorithms, beginning with a random initial population of design variables and progressing to the next generation through some form of mutation, recombination, and selection. DES is a simple scheme that uses straightforward methods for mutation, recombination, and selection. Given a set of N design parameter vectors, $\mathbf{X} = [x_1, x_2, \ldots, x_N]$, that define the population members at a particular generation, a set of N trial vectors $\mathbf{T}$ can be developed using a general mutation operator for each individual member, t_i

$$t_i = Gx_* + (1-G)x_a + \sum_{q=1}^{Q} F_q\left(x_{b_q} - x_{c_q}\right)$$

where the * subscript denotes the best performing vector in the current generation, and the a, b, and c subscripts denote randomly selected members of the population. G is the coefficient of the convex combination, F the mutation coefficient, and Q the number of differential terms. Finally, if an element of the trial vector lies outside of the specified variable bounds, the element is reset to the nearest bound.

Each trial vector then passes through the recombination stage, wherein the population of children vectors, $\mathbf{C} = [c_1, c_2, \ldots, c_N]$ is developed. Each element, j, of a particular child vector, c_i is determined by a simple recombination operator:

$$c_{n_j} = \begin{cases} t_{n_j} & \text{if } r_j \le R \\ x_{n_j} & \text{if } r_j > R \end{cases}$$

where r_j is a random number ($0 \leq r_j < 1$) and the crossover probability, R, is user defined ($0 < R < 1$).

In the selection stage, every member of the parent population is compared to its corresponding child vector. If the child vector performs better than the parent vector, the parent vector is replaced. Otherwise, the parent vector remains a member of the population and the child is rejected. A generation is complete once this process is complete for all population members.

For the most efficient optimization using DES, some amount of tuning is required to determine the best values for N, G, F, Q and R. The population size, N, should generally be 10-20 times the number of design variables, although for optimization problems with relatively few design variables and a clear, easy-to-find optimum, values as low as N=20 may provide quick convergence to the optimum. Higher values of G, F, and R tend to increase the population's rate of convergence to the design space near the best performing population member. Although this may push the population towards an optimum value, generally that optimum is a local one, and the loss of population diversity generally proves undesirable. Low values, on the other hand, tend to prevent the population from making adequate process towards any optimum. As suggested by Madavan [3.4], randomizing the values of G, F, and R typically provides good optimizer performance in the lack of extensive tuning data.

Evolutionary algorithms generally lack a method of determining convergence to the global maxima, so the user must use his/her best judgment in determining how many generations to calculate when using DES. Because of the random nature of the optimizer, the user should also not necessarily expect repeatability in results, especially when comparing results after relatively low numbers of generations. DES coupled with SQR provides a very effective means of finding global optima, however it should be noted that there usually a significant computational cost associated with this effectiveness.

3.3.2 Objective Function Calculation

Objective and constraint function calculations depend on several user inputs:

<u>variable being considered</u> – all variables calculated by UPTOP can be used in optimization or constraint functions. Further, the user will often need to define a tracking variable to perform a simple operation on an existing variable. Operators such as maximum/minimum and average values are available for use, and these operators can be applied across the entire trajectory or only user-specified segments.

<u>objective/constraint type</u> – currently, UPTOP only allows for straightforward objective or constraint functions, i.e., maximize a particular variable, subject to the value of another variable not exceeding a maximum value. For objective functions, a variable can be maximized or minimized. Additionally, a truncated maximum/minimization mode is available, which requires

a target value also be specified. In the case of a truncated maximization of variable x, the objective function, f, is

$$f(x)_i = \begin{cases} x_i & \text{if } x_i < \text{target}_i \\ \text{target}_i & \text{if } x_i \geq \text{target}_i \end{cases}$$

A constraint function, g_i, is considered satisfied when $g_i \leq 0$. In UPTOP, the constraint functions are defined as

$$g(y)_i = m\left(C_{lmm-i} - y_i\right) - t_i$$

where y is the value of the variable under consideration, C_{lim} is the constraint limit, and t_i is the constraint tolerance. m is the constraint mode; if $m = 1$, the constraint is violated if y drops below the constraint limit, and if $m = -1$, the constraint is violated if y exceeds the constraint limit. The constraint tolerance provides some leeway in the constraint status, and is mainly included in UPTOP to allow DOT to distinguish between active, satisfied, and violated constraints.

objective/constraint weighting – the DES-SQP optimizer can only optimize a single objective function. Further, DES compares population members based on a single constraint function. Therefore, when multiple objective and constraint functions are specified, the respective functions must be summed into a single objective function and single constraint function. To allow the user more control over the influence of the individual functions, a weighting value, w, may be specified, such that

$$F = \sum_{i=1}^{num\_goals} w_i f(x)_i$$

for the objective functions, and similar for the constraint functions.

when to compute the function value – the user must select the moment at which to compute the objective or constraint function value. This moment can be chosen based on time or percentage of trajectory/stage length, or tied to user-defined events in the trajectory. For instance, the user may want to constrain the altitude below a certain value at the end of the trajectory. Alternatively, the user may wish to constrain the Mach number below a certain limit until the vehicle reaches 10km in altitude. The objective and constraint functions are not computed by UPTOP until after completion of the trajectory, when full-knowledge of the vehicle states is available.

3.3.3 Member Competition

DES relies heavily on competition between existing population members and members of the child population. Therefore, it becomes important to define a set of rules for selection. For unconstrained optimization, the objective functions, F, are simply compared, and the better

performing member wins the competition. In this version of DES, the overall constraint value, G - which is the weighted sum of the individual constraint functions - is first compared. If member 1's G is less than the member 2's, member 1 wins the competition. If the values of G are equal, the objective functions are then considered as before to determine a winner.

3.3.4 Hybrid Optimization

After some experimentation with various methods, the current version of UPTOP uses a very straightforward method of combining DES with DOT. The optimization process begins with DES and progresses for a number of generations, as specified by the user. At that point, the best performing member of the population is sent to a 'front-end' subroutine used to scale the constraint gradients and reconfigure the population member for use by DOT. DOT is allowed to run to conclusion, and then restarted. The final design from DOT is then compared to the original population member, and if the new design is better, it replaces the original member. If not, the new design is randomly compared to several other members, and may replace one of those or be rejected entirely. With DOT completed, the DES continues to run for the set number of generations. The next time DOT is called, the best performing member will be sent to DOT only if it has been changed by the recent DES calls. Otherwise, a random population member is sent to DOT, and the above process repeated.

3.3.5 Parallel Optimization

Due to the nature of DES, UPTOP is well suited towards parallelization when run in optimization mode. UPTOP incorporates Message Passing Interface (MPI) to facilitate its use across multi-computer networks, and uses a self-scheduling job controller to ensure the best use of resources. Further, UPTOP makes use of multiple processors when calculating gradients in DOT, minimizing the idle time of processors throughout the entire optimization.

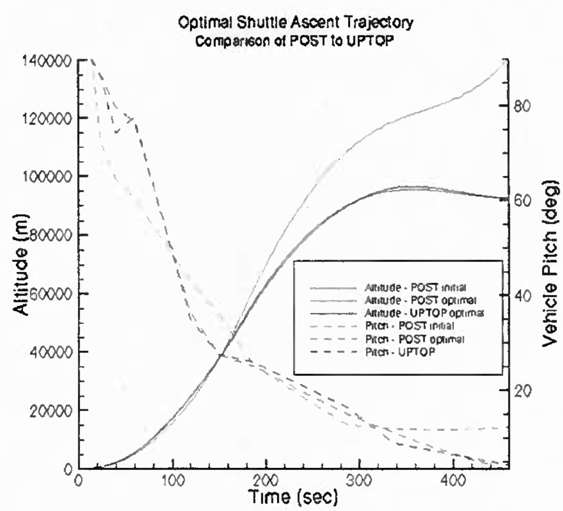


Figure 3.4 Comparison of POST to UPTOP

3.4 Validation

UPTOP has been validated against sample problems solved by Program to Optimize Simulated Trajectories (POST) [3.6] with good agreement, and although it makes sacrifices in overall computational time when optimizing, UPTOP guarantees a thorough examination of the entire design space while searching for the optimal solution.

Figure 3.4 shows the excellent agreement in the optimal Space Shuttle model ascent profiles as determined by POST and UPTOP. The POST solution reports an optimal second stage dry mass of 140,747.0 kg, whereas UPTOP reports an optimal second stage dry mass of 140,796.8 kg. Figure **Error! Reference source not found.** shows the optimal vehicle altitude and pitch profiles as functions of time, as determined by both codes. For comparison, the Figure also shows the trajectory computed by UPTOP when using the optimal POST results as input. With the exception of the discrepancy near t=50s, the optimal vehicle pitch profiles match closely.[1]

This sample problem is solved by POST relatively quickly using the projected gradient method, and requires roughly 5,000 function calls to optimize using UPTOP. Although these is a significantly greater computation expense using UPTOP, there is an additional consideration for the user of both codes. Also shown in Fig. **Error! Reference source not found.** is the initial trajectory given in the POST input deck that serves as the starting point for the POST optimization. Considering the wide bounds of the design variables, this initial trajectory should be considered to be in the neighborhood of the optimal solution, and there may be considerable effort involved in determining this initial trajectory. In general, gradient-based optimizers require an initial set of design variables, and a clear, uninterrupted path between the initial and optimal designs. Although there exists numerous methods for extracting the optimizer from local optima or even overcoming discontinuities in the design space, these methods generally increase the amount of problem-specific user tuning. UPTOP, on the other hand, does not require the knowledge of an initial trajectory, and for more complex optimization problems, this tradeoff may make UPTOP more useful.

More information regarding this validation case is provided in the Usage Manual, and additional information regarding the validation of UPTOP can be found in Ref. [3.2].

[1] The differences in pitch angles in that region may be due to the fact that UPTOP does not account for thrust vectoring losses due to the solid rocket booster gimbaling. Such a feature is currently being developed for UPTOP.

Chapter 4 Thermal Protection System Optimization (TPSOPT) Program

The development of TPSOPT was supported by a two-year AFRL contract [4.1] with the goal of developing a automated design software for Thermal Protection System (TPS) optimization of hypersonic flight vehicles. Using a feasible direction optimization method, TPSOPT minimizes the weight of the TPS while subjected to the temperature constraints at each layer of the TPS. TPSOPT equip with a TPS material library that contains several hundreds of the thermal properties of various TPS from which the users can select to construct a multi-layer thermal protection system. It also has several built-in TPS structural arrangement concepts such as slab, radiation, gap, honeycomb, corrugated standoff, Z-standoff, ablator subliner, etc. to reduce the user's burden for input set-up.

In order to streamline TPSOPT with UCDA and UPTOP, several modifications are made to the original TPSOPT: (1) the surface mesh of the vehicle is automatically imported from UCDA; (2) the trajectory along which the heat flux at each surface mesh is computed is automatically imported from UPTOP; and (3) the aerothermodynamic methodology of the MINIVER code [4.2] is incorporated in TPSOPT to compute the heat flux on the surface mesh at each time step of the trajectory.

4.1 Optimization Strategy

Because the surface mesh defined by UCDA is divided by several patches as the one shown in Figure 4.1, TPSOPT optimizes the TPS on each patch individually. This is to say that on each patch, a TPS with the same type of structure but with varying thickness distribution of each layer can be specified. In order to ensure the smoothness of the optimized TPS thickness distribution over the patch, only some selected panels, called design panels, participated the optimization computation, while other panel's thicknesses are interpolated through the design panel's thicknesses. Polynomial interpolation is employed which serves as a set of shape functions over those selected panels. Thus, the design variables are the coefficients of those shape functions;

not the thickness of the TPS layers. This approach can largely reduce the number of design variables in the optimization problems and can ensure the smoothness of the thickness distribution of the TPS thickness.

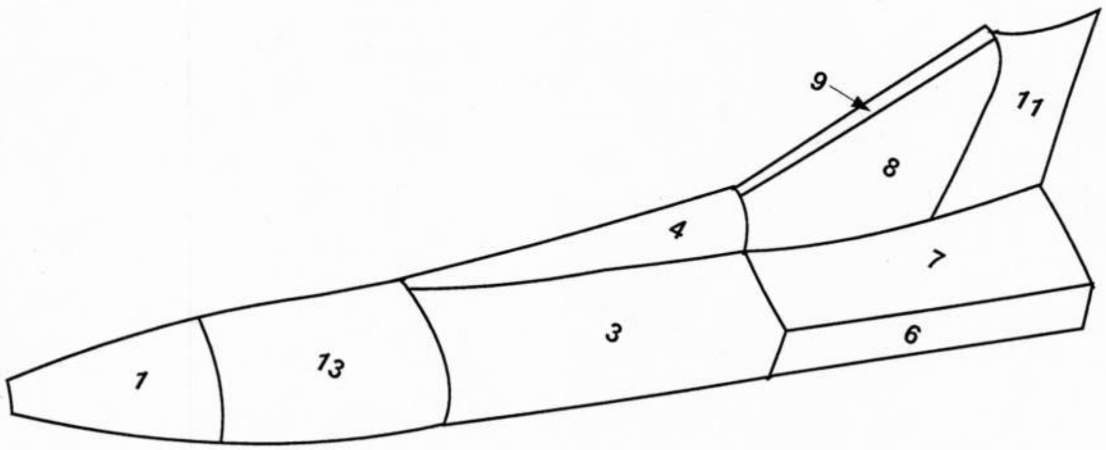


Figure 4.1 Patches of the surface Mesh for optimization

The panels within one patch are classified into three types of panels, as shown in Figure 4.2, namely the design variable patches (marked using ellipses), the hot panels (marked using diamonds), and the thickness panels (all panels). The thickness panels are subjected to the thickness constraints where the upper and lower limits of the thickness of each TPS layer are imposed. The hot panels are those panels on which the temperature distributions through the thickness of the TPS are computed and temperature constraints of each layer are imposed. Thus, the heat conduction computation is only performed for those hot panels to reduce the computational time. The design variable panels are a subset of the hot panels. They are used to define a set of shape functions to represent the thickness distribution of the TPS over the entire patch. Thus, the number of design variables becomes the coefficients of the shape functions, greatly reducing the unknowns of the optimization problem.

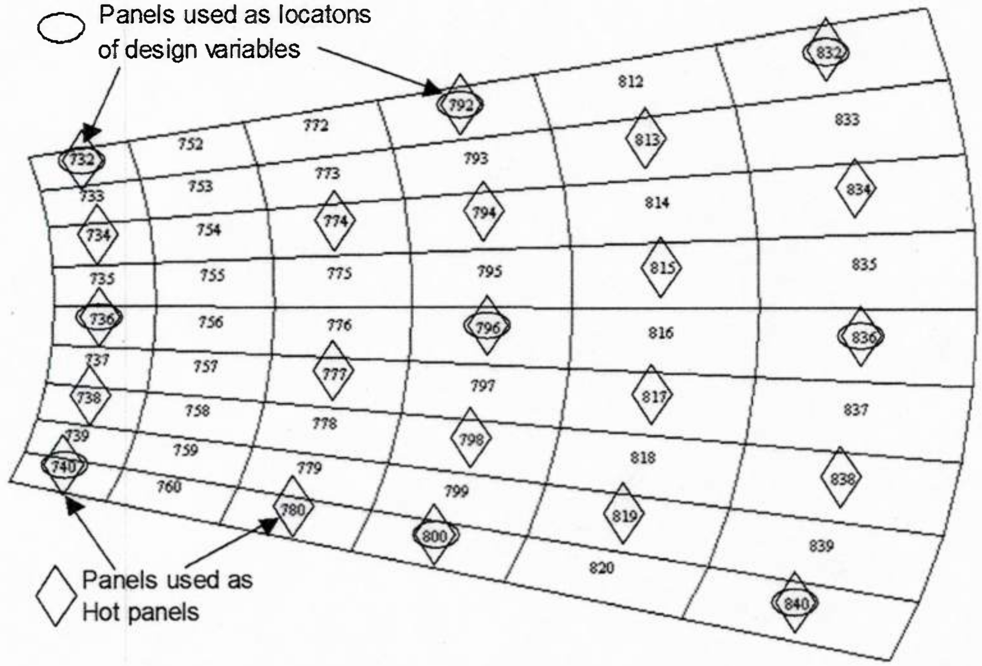


Figure 4.2 Different panels over a patch

4.2 Polynomial Approximation of Thickness

In order to reduce the number of design variables, rather than selecting the thickness of the TPS on all panels within a patch as the design variables, the thickness of each layer over the patch is expressed as a polynomial of coordinates as follows

Linear variation:
$$h = a_0 + a_1 x + a_2 y + a_3 z \tag{4.1}$$

Quadratic variation:
$$\begin{aligned} h = a_0 + a_1 x + a_2 y + a_3 z + a_4 x^2 + a_5 y^2 \\ + a_6 z^2 + a_7 xy + a_8 yz + a_9 yz \end{aligned} \tag{4.2}$$

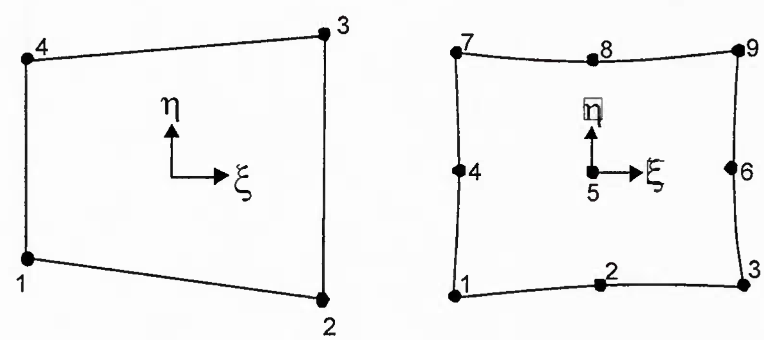
It is not the thickness, h, over each panel to be taken as the design variables. Instead, the coefficients, a_i, are defined as design variables. Once these coefficients are determined, the thickness over each panel can be obtained by substituting the coordinates of each panel into

Equation (4.1) or (4.2). This strategy can result in a smooth variation of thickness over the patch and the number of design variables can be reduced significantly.

Although Equations (4.1) and (4.2) are easy to understand conceptually, the design variables, a_i, have no physical meaning and are not convenient to be numerically implemented. In order to overcome this disadvantage, shape functions used in the finite element method and in the boundary element method are adopted in TPSOPT.

4.3 Shape Functions for Interpolation of Thickness

Shape functions are defined over an "element" characterized by element nodes (Figure 4.3).



(a) (b)

Figure 4.3 Quadrilateral elements: (a) linear, (b) quadratic

Over an element, the thickness h at point (ξ, η) can be expressed in terms of the nodal values of h [4.3] as:

$$h(\xi,\eta) = \sum_{\alpha=1}^{M} N_{\alpha}(\xi,\eta) h^{\alpha} \tag{4.3}$$

where ξ and η are curvilinear coordinates, usually normalized to a value in the range of -1 to $+1$, h^{α} is the thickness of the α-th node over the element under consideration and M is the number of nodes over the element. The shape function for linear variation can be expressed as:

$$
\begin{aligned}
N_1(\xi,\eta) &= \frac{1}{4}(1-\xi)(1-\eta) \\
N_2(\xi,\eta) &= \frac{1}{4}(1+\xi)(1-\eta) \\
N_3(\xi,\eta) &= \frac{1}{4}(1+\xi)(1+\eta) \\
N_4(\xi,\eta) &= \frac{1}{4}(1-\xi)(1+\eta)
\end{aligned}
\tag{4.4}
$$

and for quadratic variation are:

$$
\begin{aligned}
N_1(\xi,\eta) &= \frac{1}{4}\xi(1-\xi)\eta(1-\eta) \\
N_2(\xi,\eta) &= -\frac{1}{2}(1-\xi^2)\eta(1-\eta) \\
N_3(\xi,\eta) &= -\frac{1}{4}\xi(1+\xi)\eta(1-\eta) \\
N_4(\xi,\eta) &= -\frac{1}{2}\xi(1-\xi)(1-\eta^2) \\
N_5(\xi,\eta) &= (1-\xi^2)(1-\eta^2) \\
N_6(\xi,\eta) &= \frac{1}{2}\xi(1+\xi)(1-\eta^2) \\
N_7(\xi,\eta) &= -\frac{1}{4}\xi(1-\xi)\eta(1+\eta) \\
N_8(\xi,\eta) &= \frac{1}{2}(1-\xi^2)\eta(1+\eta) \\
N_9(\xi,\eta) &= \frac{1}{4}\xi(1+\xi)\eta(1+\eta)
\end{aligned}
\tag{4.5}
$$

Only linear and quadratic shape functions are given above. In the TPSOPT program, a shape function family with n×m nodes has been coded, in which n and m are the numbers of the nodes along the ξ and η direction, respectively.

The shape functions have an important feature [4.4] that is when the curvilinear coordinates (ξ, η) take nodal values, the shape function of that node is 1, while other shape functions are 0. This feature makes the h^{α} in Equation (4.3) to be the value of the thickness, h, at the α-th node. In the optimization computation, the nodal values h^{α} of the thickness are taken as design variables, while the thicknesses of the other panels are interpolated using Equation (4.3).

4.4 TPS Optimization Formulations

Figure 4.4 depicts a typical TPS design problem, which consists of n layers of different TPS materials. This design process can be automated by formulating an optimization problem to minimize the following objective function:

$$F = \sum_{l=1}^{L} \sum_{p=1}^{P} A_p \rho_p^l h_p^l \tag{4.6}$$

where

A_p	is the area of the panel p.
ρ_p^l	is the density of the panel p on layer l.
h_p^l	is the thickness of the panel p on layer l.
L	is the number of layers.
P	is the number of all panels over the patch.

The thickness h_p^l can be expressed with the thickness of element nodes by applying Equation (4.3) to each layer of the patch, as follows

$$h_p^l = \sum_{\alpha=1}^{M_l} N_\alpha^l (\xi_p, \eta_p) h^{\alpha l} \tag{4.7}$$

where

$h^{\alpha l}$	is the thickness of node α on layer l.

$N_\alpha^l(\xi_p,\eta_p)$ is the value of shape function α on layer l for panel p.

ξ_p and η_p is the intrinsic coordinates of panel p.

M_l is the number of element nodes on layer l.

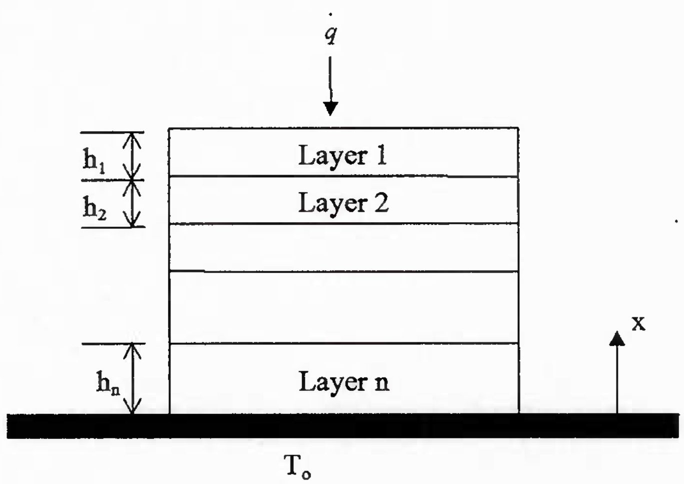


Figure 4.4 Typical TPS sizing problem

This optimization problem can be solved by linking a TPS analysis code such as the MINIVER/EXITS [4.5] module with an optimization driver like the usable/feasible direction method imbedded in ADS [4.6]. In this methodology, the nodal thickness, $h^{\alpha l}$, on each layer is taken as design variables which are related to the objective function by Equation (4.6). The optimization is performed by minimizing the objective function, F, shown in Equation (4.6) subjected to the following constraints.

Thickness constraints:

$$H_{\min}^l < h_p^l < H_{\max}^l \tag{4.8}$$

$$T_{nms}^\beta < T_{\max}^\beta \tag{4.9}$$

where

$H^l_{\min}$ and $H^l_{\max}$ is the allowable minimum and maximum thickness for layer l.

T^β_{nms} is the temperature of hot panel n on the side s for trajectory m at the heat point β.

$T^\beta_{\max}$ is the allowable maximum temperature of layer heat point β.

The temperature distribution through the thickness is computed by the thermal analysis software MINIVER/EXITS.

In computation, gradients of the objective function and the constraints are used to accelerate the iteration convergence. They can be easily obtained from Equations (4.6) and (4.7) as

$$\frac{\partial F}{\partial h^{\alpha l}} = \sum_{p=1}^{P} A_p \rho_p^l N_\alpha^l(\xi_p, \eta_p) \tag{4.10}$$

$$\frac{\partial h_p^l}{\partial h^{\alpha l}} = N_\alpha^l(\xi_p, \eta_p) \tag{4.11}$$

$$\frac{\partial T_{nms}^\beta}{\partial h^{\alpha l}} = N_\alpha^l(\xi_n, \eta_n) \frac{\partial T_{nms}^\beta}{\partial h_n^l} \tag{4.12}$$

where ξ_n and η_n are intrinsic coordinates of the hot panel n and $\partial T_{nms}^\beta / \partial h_n^l$ is determined by running MINIVER/EXITS.

4.5 Determination of Intrinsic Coordinates for Panels

In the above equations, the intrinsic coordinates, (ξ_p, η_p) and (ξ_n, η_n), for thickness panels and for hot panels are used. Since the shape function $N_\alpha(\xi, \eta)$ is a nonlinear function of the intrinsic coordinates ξ and η (see Equation (4.5)), an iteration process is employed to determine the intrinsic coordinates by given global coordinates of a panel [4.7].

For convenience here, we denote the complete set of intrinsic coordinates by the notation ξ_i, signifying the two intrinsic axes ξ and η on an element (i=1-2). With this notation, the global Cartesian coordinates at the center of the panel, p, can be expressed in terms of the nodal coordinates in the form:

$$x_j^p = \sum_{\alpha=1}^{M} N_\alpha(\xi_i) x_j^\alpha \tag{4.13}$$

where x_j^α are the coordinates of element nodes. First, we begin with some starting guess (ξ_i^0) of the intrinsic coordinates of the point p and we let r_j^0 be the resulting error of Equation (4.13). Now, the notation R_j^k, ξ_i^k is used to denote the values after the k-th iteration, that is:

$$R_j^k = \sum_{\alpha=1}^{M} N_\alpha(\xi_i^k) x_j^\alpha - x_j^p \tag{4.14}$$

To obtain improved values of ξ_i, we expand this equation using Taylor's theorem:

$$R_j^{k+1} = R_j^k + \frac{\partial R_j}{\partial \xi_i}\Delta\xi_i = R_j^k + \sum_{\alpha=1}^{M} \frac{\partial N_\alpha}{\partial \xi_i} x_j^\alpha \Delta\xi_i \tag{4.15}$$

where $\Delta\xi_i$ are the changes in ξ_i. Setting R_j^{k+1} equal to zero, we obtain (in matrix form), the Newton-Raphson iterative scheme:

$$[K^k]\{\Delta\xi\} = -\{R^k\} \tag{4.16}$$

where the coefficients of the matrix are:

$$[K_{ji}^k] = \sum_{\alpha=1}^{M} \frac{\partial N_\alpha}{\partial \xi_i} x_j^\alpha \tag{4.17}$$

Since there is one less intrinsic coordinate than global coordinate and hence Equation (4.16) is over-prescribed. The least-squares approximation will suffice, i.e.:

$$[K^k]^T[K^k]\{\Delta\xi\} = -[K^k]^T\{R^k\} \tag{4.18}$$

where the superscript T denotes the matrix transpose. Solving for $\{\Delta\xi\}$, the current values of ξ_i can be updated, thus:

$$\xi_i^{k+1} = \xi_i^k + \Delta\xi_i \tag{4.19}$$

These calculations (Equations 4.14 - 4.19) are iterated until satisfactory convergence (of R^k) is attained. Typically, three iterations are sufficient to attain sufficient convergence, given an initial guess at the element centroid.

4.6 Computation of Sensitivity Matrices Using Complex Variable Differentiation Technique

To perform an optimization computation using feasible direction method, it is required to compute the derivatives of the temperature with respect to the thickness. Many techniques, such as Finite Difference Method (FDM), Automatic Differentiation (ADIFOR), Symbolic Differentiation, or the Complex Variable Differentiation (CVD) technique, can be adopted and applied to the MINIVER/EXITS module to provide sensitivity. Among them, the CVD

technique is selected because by comparison it is a "numerically-exact" method and requires the least programming effort [4.8].

The Complex Variable Differentiation (CVD) technique was first originated by Lyness and Moler [4.9]. In the complex variable approach, the variable x of a real function $f(x)$ is replaced by a complex one, $x+i\Delta h$. For small Δh, $f(x+i\Delta h)$ can be expanded into a Taylor's series as follows:

$$f\left(x+i\Delta h\right)=f\left(x\right)+i\Delta h\frac{d\ f}{dx}-\frac{\Delta h^2}{2}\frac{d^2 f}{dx^2}-i\frac{\Delta h^3}{6}\frac{d^3 f}{dx^3}+\frac{\Delta h^4}{24}\frac{d^4 f}{dx^4}\cdots \tag{4.20}$$

The first and second derivatives of the above equation can be expressed as:

$$\frac{df}{dx}=\frac{Im\left[f\left(x+i\Delta h\right)\right]}{\Delta h}+O\left(\Delta h^2\right) \tag{4.21}$$

$$\frac{d^2 f}{dx^2}=\frac{2\left[f\left(x\right)-Re\left(f\left(x+i\Delta h\right)\right)\right]}{\Delta h^2}+O\left(\Delta h^2\right) \tag{4.22}$$

where the symbols "*Im*" and "*Re*" denote the imaginary and real parts, respectively. From Equations (4.20) and (4.21), it can be seen that the derivatives using the CVD approach only require function evaluations. This feature is very attractive particularly when the function is sufficiently complicated, in which case to obtain an analytic derivative is cumbersome and error-prone. Unlike the finite difference method, where the accuracy of the derivative depends on the step-size, Equation (4.21) shows that the first derivative does not involve differencing two functions followed by magnification of the subtraction error (because of the division by the step size Δh). In fact, no cancellation errors exists for the first derivative in the CVD technique, thus the first derivative is step-size independent. Note that the second derivative in Equation (4.22) is prone to cancellation errors (because of the subtraction of two close numbers), but is not used here.

Because CVD does not introduce cancellation (round off) error for the first derivative, the step-size, Δh, can be chosen as small as the machine zero, e.g., $\Delta h = 10^{-30}$. Hence, the truncation error due to Taylor's series of the order of $\Delta h^2 = 10^{-60}$ that approaches essentially a machine zero in a 32-bit computer. For first derivative, CVD does not seem to introduce any approximation in its numerical differentiation; rather it is a nearly "numerically-exact" differentiation technique.

To incorporate CVD into the MINIVER/EXTIS module for sensitivity is rather straightforward. One can simply declare all variables in the code as complex variable and introduce a small imaginary perturbation ($i\Delta h = i \times 10^{-30}$) in the design variable, h_i. Division of the imaginary part of the temperature time history in each layer by Δh yields the sensitivity.

4.7 Optimization Examples

To validate the accuracy of the sensitivity MINIVER/OPT, two examples are given in this section. The first one is concerned with a single panel sizing optimization which can clarify the design concept presented in this chapter. The second example is focused on the performance of the TPSOPT software in the overall vehicle design.

4.7.1 Example 1: Advanced Flexible Reusable Surface Insulation

We select the constructed prototypical TPS system using an AFRSI (Advanced Flexible Reusable Surface Insulation) module, Figure 4.5.

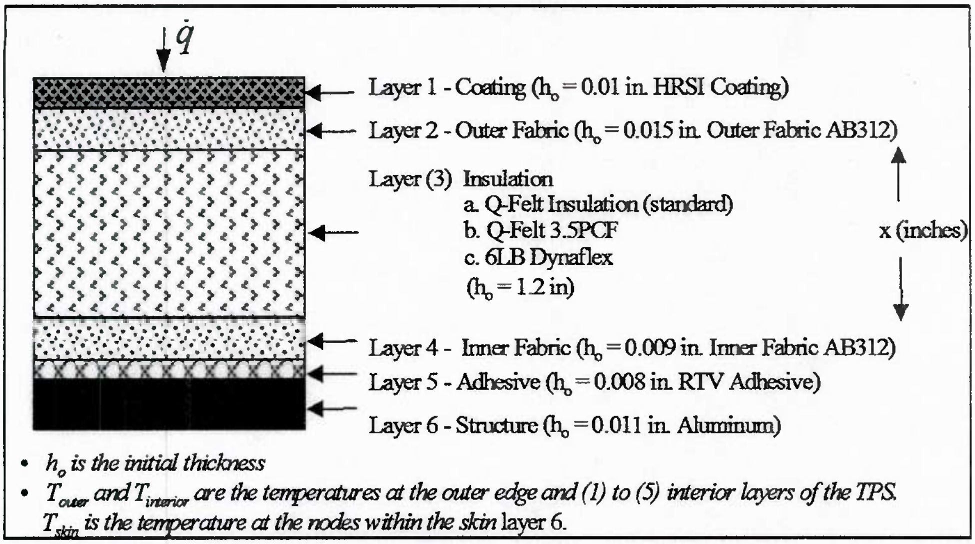


Figure 4.5 Description of the model TPS system

With the given heat/flux $\dot{q}$ at time history depicted in Figure 4.6, we focus on the temperature sensitivity of layer 6. The sensitivity $\partial T_6 / \partial h_3$, which precisely corresponds to the temperature change at the aluminum structure due to the thickness perturbation of the Q-Felt insulation material (layer No. 3), computed by TPSOPT is shown in Figure 4.7. The negative values of the sensitivity indicate a decrease of temperature due to the increase of thickness; as expected. Comparing to the results of CVD, the relative error of the sensitivity computed by FDM with various step sizes is depicted in Figure 4.8. It can be seen that the error of FDM decreases while the step size decreasing. But with a very small step size ($\Delta h = 10^{-8}$), the error increases, showing that the accuracy of FDM is step-size dependent.

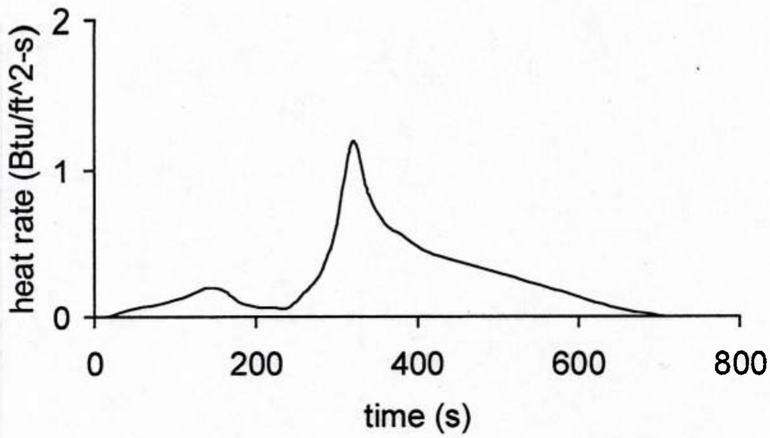


Figure 4.6 A given heat flux time history

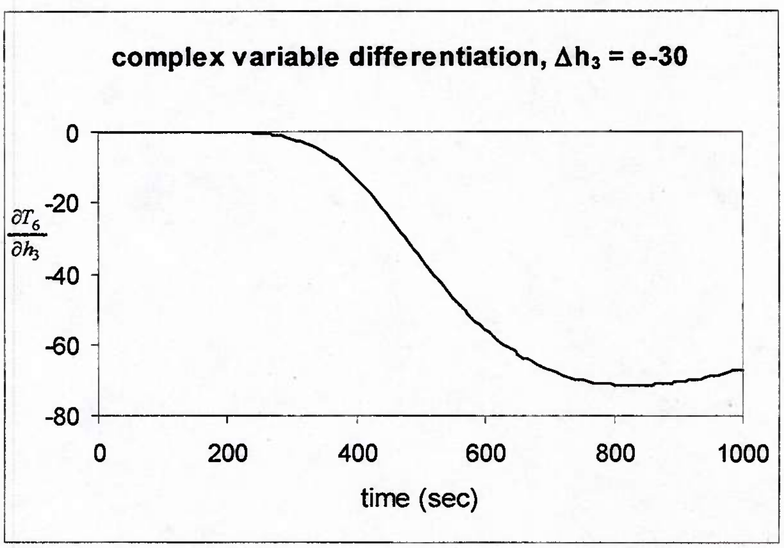


Figure 4.7 Sensitivity $\partial T_6/\partial h_3$ by TPSOPT in the entire history

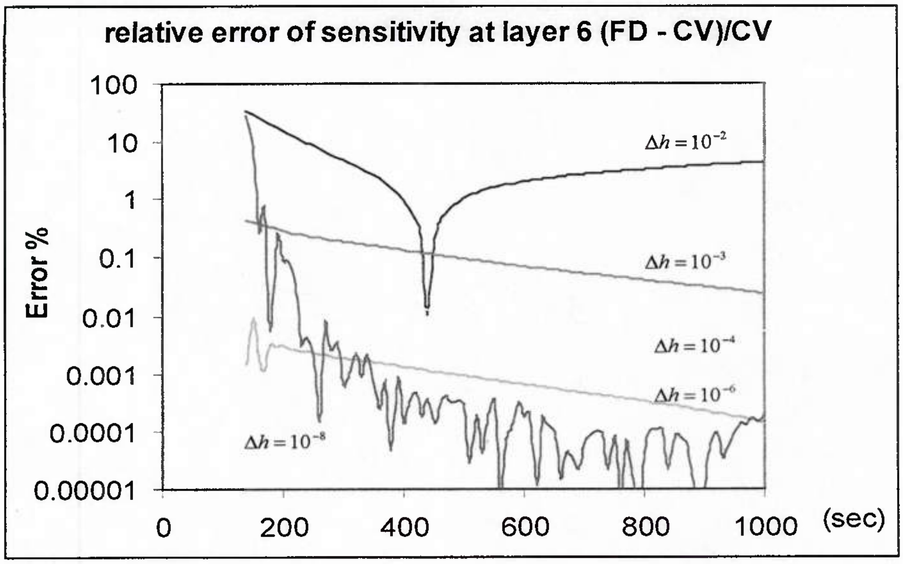


Figure 4.8 Relative error of FDM and CVD for sensitivity $\partial T_6 / \partial h_3$

Table 4.1 Case A optimization Results

Layer	Material and Temp limit (°F)	Density (lbm/ft^3)	Specific heat (But/lbm°F)	Initial thick-ness (in)	$T_{\max}$ in layer (°F)	Optimized thickness (in)
1	HRSI Coating 2300	104	0.20	0.01	705.2	0.0072
2	AB312 Fabric 2024	61.5	0.166	0.015	704.9	0.0072
3	Q-Felt 1800	3.5	0.1875	1.2	701.6	0.66849
4	AB312 Fabric 2024	61.5	0.166	0.009	300.0	0.0072
5	RTV-560 550	88	0.285	0.008	300.0	0.0072
6	Aluminum 300	173	0.22	0.011	300.0	0.011

- *Layer Thickness: upper bound 1.0", lower bound 0.0072"*
- *Given Input heat flux $\dot{q}$, see Figure 4.6*
- *Optimized Weights $W_{initial}$ = 0.777 lbm/ft^2, W_{final} = 0.543 lbm/ft^2*

Shown in Table 4.1 are the optimization results of the AFRSI TPS system (Case A). In this optimization problem, the thicknesses of the first five layers are defined as design variables with

initial thickness and maximum operational temperature shown in Table 4.1. The upper bound and lower bound of these five design variables are assumed to be 1.0" and 0.0072", respectively. The thickness of the aluminum layer (layer 6) remains unchanged because it represents the load-carry structure and is not a part of the TPS system. It can be seen that all design variables reach the lower bound (0.0072") except the Q-Felt layer. This is expected because the Q-Felt layer has the lowest density and thermal conductivity that provides the highest thermal insulation capability with least structural weight.

Table 4.2 Case B Optimization Results

Layer	Material and Temp limit (°F)	Density (lbm/ft^3)	Specific heat (But/lbm°F)	Initial thick-ness (in)	T_{max} in layer (°F)	Optimized thickness (in)
1	HRSI Coating 2300	104	0.20	0.01	814.5	0.0072
2	AB312 Fabric 2024	61.5	0.166	0.015	814.3	0.0072
3	Q-Felt 1800	3.5	0.1875	1.2	810.0	0.6000
4	AB312 Fabric 2024	61.5	0.166	0.009	300.0	0.0072
5	RTV-560 550	88	0.285	0.008	300.0	0.02705
6	Aluminum 300	173	0.22	0.011	300.0	0.011

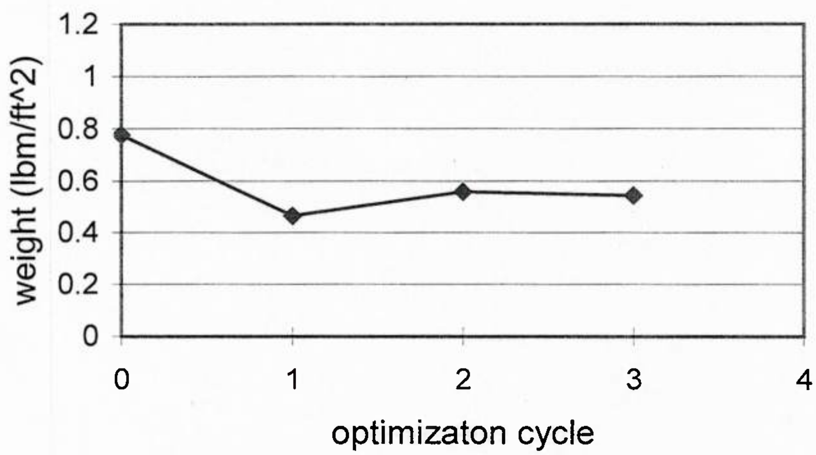
- *Layer Thickness: upper bound 0.6", lower bound 0.0072"*
- *Given Input heat flux 1.5x $\dot{q}$, see Figure 4.6*
- Optimized Weights $W_{initial}$ = 0.777 lbm/ft^2, W_{final} = *0.668 lbm/ft^2*

Table 4.2 presents the optimization results of the same AFRSI TPS system but with a magnified heat flux (by a factor of 1.5) and a reduced upper bound of layer thickness (Case B). The optimized result shows that the thickness of the Q-Felt layer reaches the upper bound and that of the RTV-560 layer become 0.02705" while the thickness of other layers remain at the lower bound. This indicates that because of the higher heat flux input, the Q-Felt layer with the upper bound thickness alone is not sufficient to satisfy the temperature constraints at all layers. Other than the Q-Felt layer, the next best thermal protection material is the RTV-560 layer because of

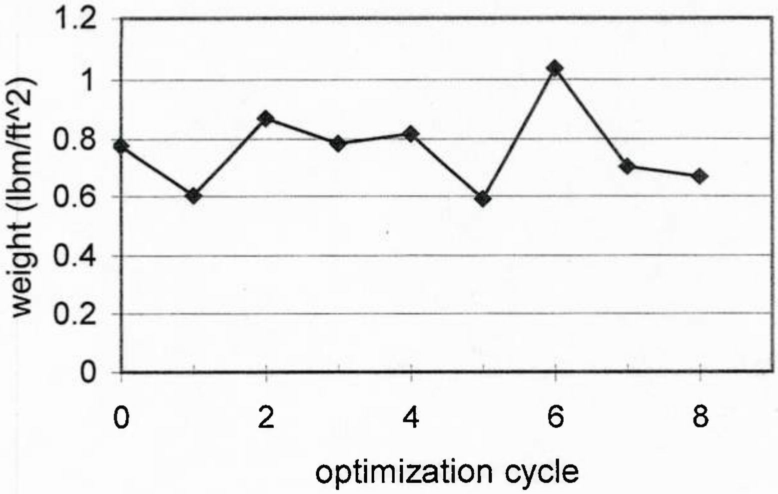
its high specific heat (c_p) value. Although, the RTV-560 layer has a high density ρ which may not be structurally efficient, however, its higher ρc_p value can offer a good thermal protection capability. Indeed, TPSOPT can detect this capability and thereby increase the thickness of the RTV-560 layer from the lower bound to 0.02705".

Figure 4.9 presents the weight variance versus design cycles during the optimization process. Note that in Case A the nominal heat-flux achieves optimized weight with 3 cycles in 4.5 minutes; whereas in Case B (with 1.5 times heat-flux) takes 8 design cycles in 6.5 minutes.

Figure 4.10 presents the time history of the temperature of Case B of the aluminum layer during its eight optimization design cycles. With the maximum operational temperature being 300°F of the aluminum as one of the design constraints, it can be seen that the initial thickness is over-designed because its maximum temperature is only approximately 230°F. Meanwhile, an intermediate design offers a minimum weight but its maximum temperature (400°F) violates the constraint. The maximum temperature of the final design is exactly 300°F, indicating that it is an optimum design.



(a) Case A with a given $\dot{q}$ (in 263 Sec)



(b) Case B with 1.5x $\dot{q}$ (in 396 Sec)

Figure 4.9 Weight variation of the modeled TPS system (AFRSI) during optimization

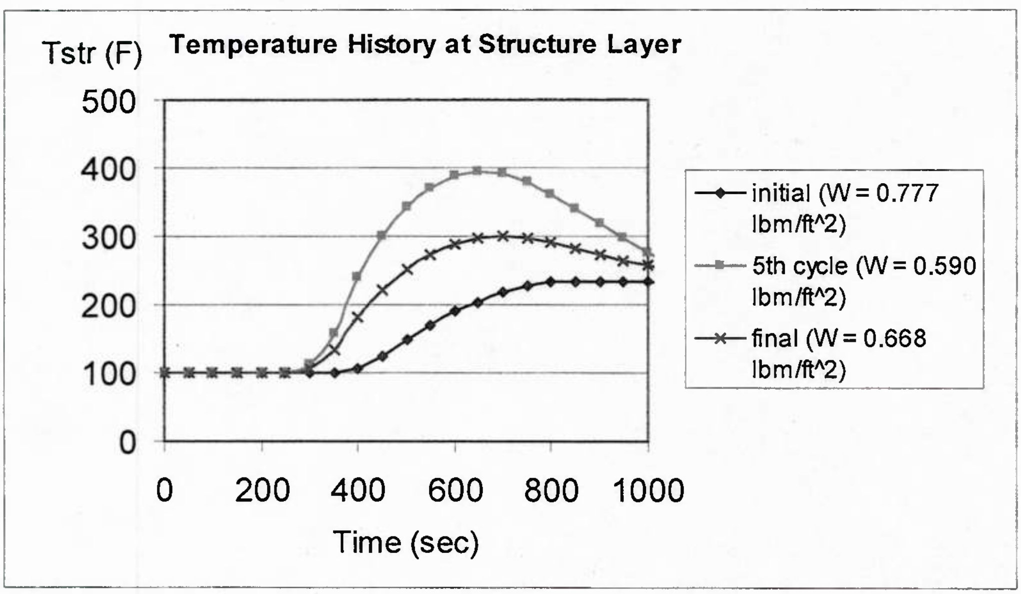


Figure 4.10 Case B temperature history at the structure layer (layer 6) during the optimization process

4.7.2 Example 2: TPS Design on the X-34

For the demonstration of the capability in handling complex configurations, TPSOPT is applied to the full configuration of the X-34 whose surface is divided into 14 patches as shown in Figure 4.1. Two types of TPS structural arrange concepts are selected; one called TPS (A) for those patches located on the nose and leading edges and the other called TPS (B) for those patches on the fuselage and wing surfaces.

These structural arrangement concepts are shown in Figure 4.11. In Figure 4.12, it can be seen that the final optimization thickness of TPS on patches in the nose region (Patches 1 and 2) is about one order of magnitude thinner than its initial thickness. The optimized total TPS weight is found to be reduced by 22% terminated after the 20th design cycle while satisfying all TPS temperature constraints (Figure 4.13).

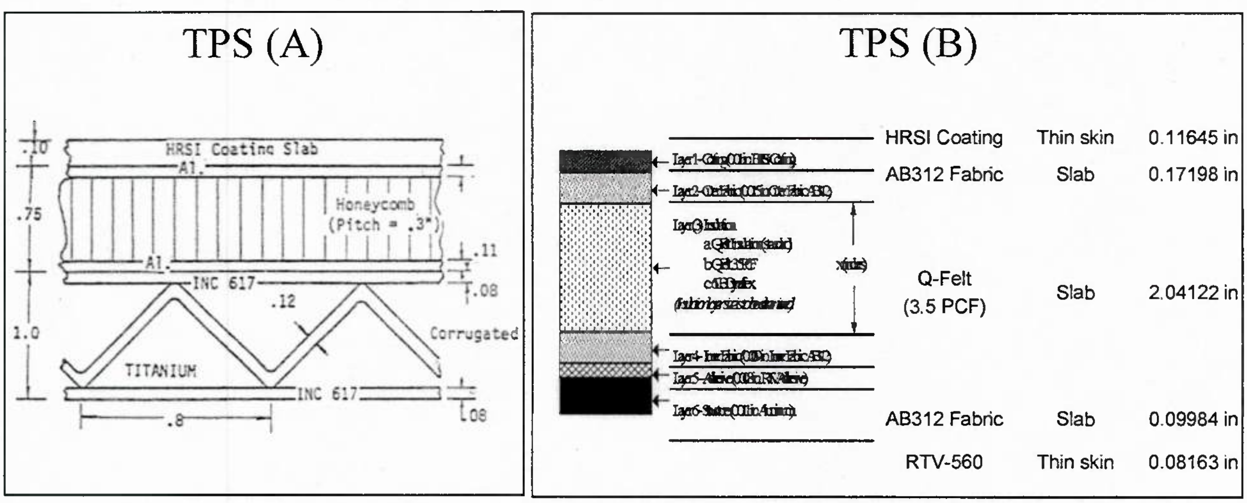


Figure 4.11 Two TPS structural arrangement concepts

TPS-(A)

Position	T/L
(1)	0.0061
(2)	0.0052
(3)	0.0048
(4)	0.0041
(5)	0.0049
(6)	0.0046

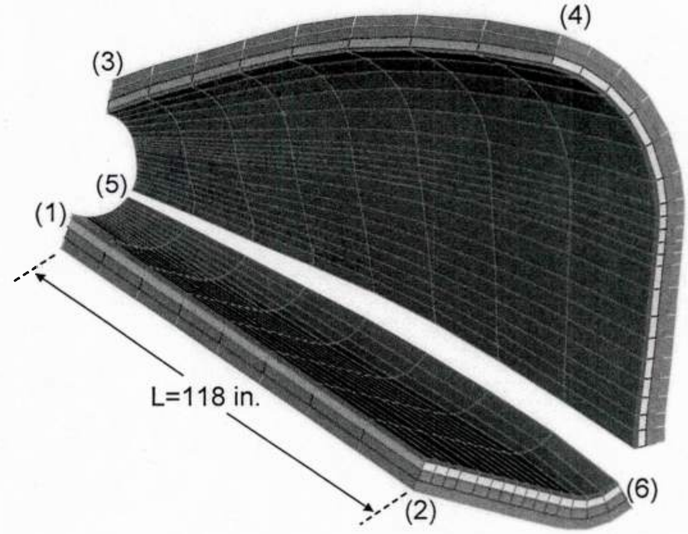


Figure 4.12 Optimal thickness for patches 1 and 2

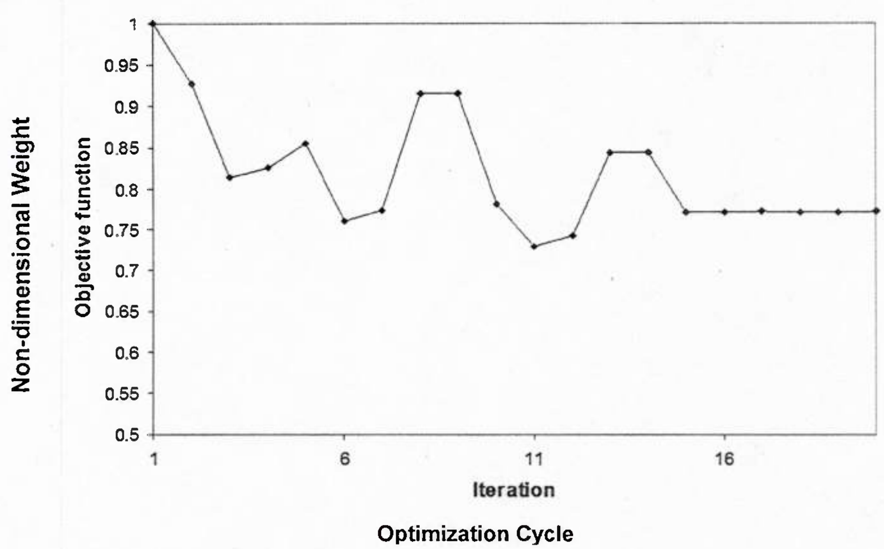


Figure 4.13 Iteration history of the objective function during optimization process

Chapter 5 Structural Modal Base (SMB) Program

The purpose of this Structural Modal Base (SMB) module is to minimize the weight of the structural skin while subjected to the stress constraints at each axial station along the vehicle using a fully stressed design (FSD) method. These stress constraints are evaluated by applying the aerodynamic loads computed based on the trajectory provided by UPTOP with an assigned load factor to simulate the worst loads condition. The optimized skin weight is used to update the total vehicle weight for the next design cycle. In addition, SMB computes the structural natural frequencies and their corresponding mode shapes that are used by the TRIM and ASE modules to include the structural flexibility effects in the analysis.

To this end, the structure is simplified to a simple beam structure with free-free support. The cross section of the beam at each axial station is assumed to be a rectangular box whose width and height are determined from the surface mesh provided by UCDA. The non-structural masses are obtained from the vehicle weight calculated by UCDA and distributed at each nodes along the beam. The design variables to be determined by the fully stressed design method are the skin thicknesses of the rectangular box at each axial station. This beam approximation of the structure is illustrated in Figure 5.1.

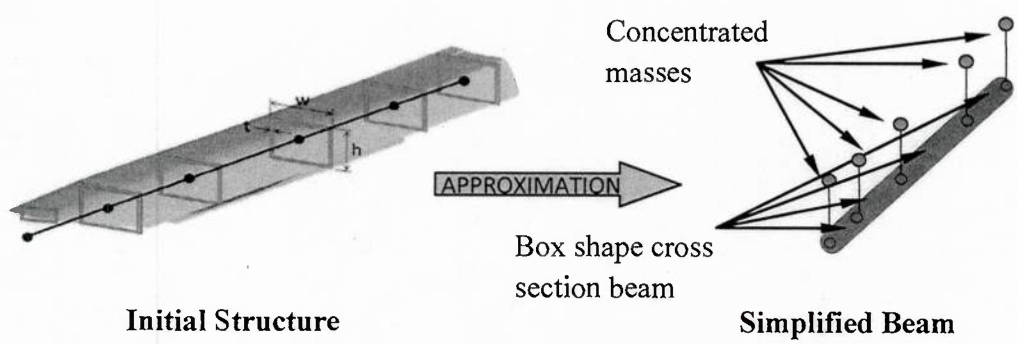


Figure 5.1 Beam approximation

Figure 5.2 shows the total program architecture of SMB. There are generally 8 steps involved in the SMB computation described as follows:

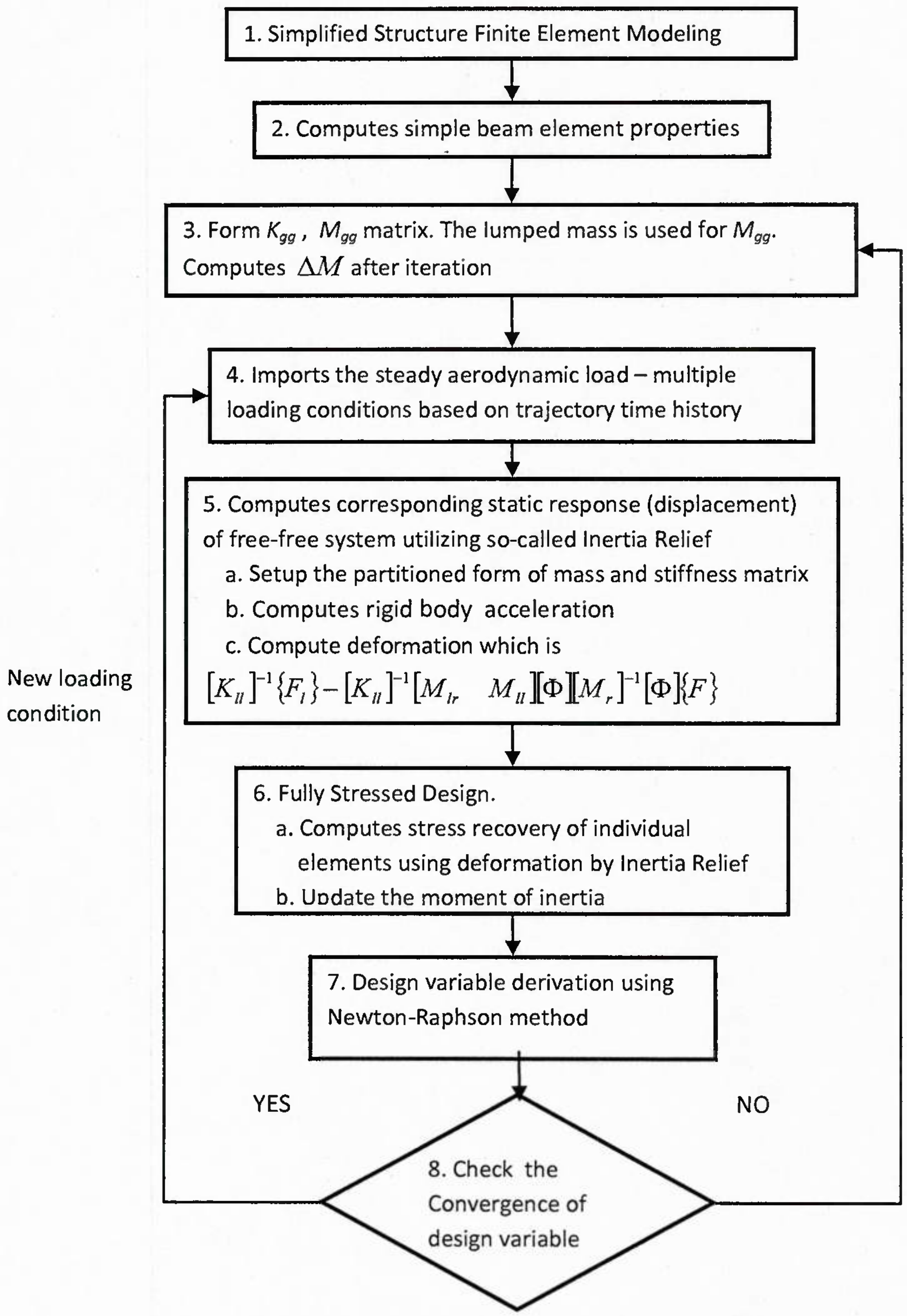


Figure 5.2 Flow chart of SMB module

(1) Finite element modeling

For the finite element modeling, the structure is discretized first where within each axial station of the discretized structure; the cross section is simplified to have an approximate and constant width, height and length. Having considered the proper meshing size for the convergence, those given section length are directly used for the beam finite element model meshing.

For the mass element matrix composition, whole structural and non-structural masses are lumped into one value and then it is divided in proportion to each element volume and distributed to each section.

(2) Beam property computation

Here, in the finite element modeling, the beam neutral axis matches the x axis. Consequently the area moments of inertia with respect to y and z axis are required. Based on the geometry information from the UCDA the beam properties are determined. All the beam properties are updated after the fully stressed design (FSD). Material property is considered homogeneous for whole structure.

(3) Element stiffness/mass matrix construction

Using those beam properties, the stiffness matrix is computed. The mass matrix is adjusted due to the addition/reduction of the thickness after FSD process, see Equation (5.1). The Euler beam theory is used for the stiffness matrix because of the unavailability of the area factor for shear in the FSD.

$$\begin{aligned} M^i_{new} &= \\ M^i_{init} &+ \{(2 * t^i_{new} + w^i) * (2 * t^i_{new} + h^i) - (2 * t_{init} + w^i) * (2 * t_{init} + h^i)\} * l^i * \rho \end{aligned} \tag{5.1}$$

M^i_{new} is the updated mass for the i^{th} element

M^i_{init} is the lumped initial mass

t^i_{new} is the new design variable of i^{th} element

h^i is the height

w^i is the width

l^i is the length

ρ is the structure material density

(4) Load import

Initially the aerodynamic load is distributed on the surface but here those are converted and given as equivalent concentrated loads at nodes. The designed thickness must satisfy the stress constraints under all the loading conditions along the trajectory given by UPTOP with an assigned load factor to simulate the worst loading conditions. In order to do so, except the first loading condition, at each load condition the thickness of the box at each axial station is only allowed to increase; thus avoiding the possible violation of the stress constraint.

(5) Response computation – Inertia Relief

Structure has the free-free boundary condition to simulate the free flight condition. This implies that without considering the inertia force by those rigid body motions, the stiffness matrix of the beam finite element model is singular. This singularity in the stiffness matrix can be removed by using the inertia relief approach. The first grid point is used as the support point in this inertia relief approach.

(6) Fully stressed design algorithm

The cross section of each beam element is assumed to be constant. Thus, the number of the total design variables is the same as the element number in this structure finite element model. Those design variables are updated by the stress ratio in the FSD algorithm. Because of the compatibility, the design variable could not reach the value satisfying the requirement without iteration. The updated design variable is compared with the minimum requirement. If it is less than the requirement, the minimum requirement is substituted for the optimized value.

(7) Design variable derivation from the moment of inertia

The relationship between the thickness of the box shape cross section and the area moment of inertia is a 3rd order polynomial. To compute the skin thickness from the moment of inertia requires an iterative search algorithm. Here, a Newton-Raphson method is used.

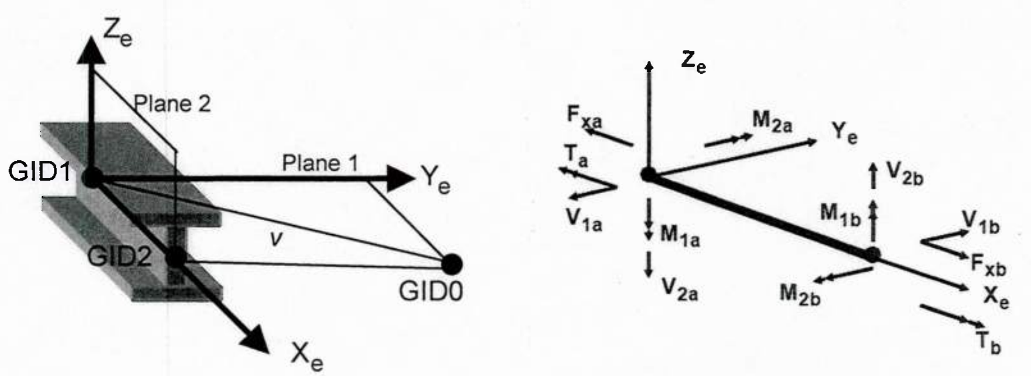
(8) Check the convergence

The difference between the updated value and previous design variable value is computed to check the convergence by a small tolerance. If it is not converged, the whole process of analysis and FSD are all repeated until the change of each design variable between two consecutive iterations is within such a tolerance.

In summary, the whole routine is mainly composed of 'finite element modeling', 'Inertia Relief computation', and 'Fully-Stressed Design algorithm'. Those processes are explained in detail in the following.

5.1 Finite Element Modeling

The finite element model shown in Figure 5.3 is a beam model along a straight line. It includes extension, torsion and bending in two perpendicular planes with associated transverse shear properties and may carry bending, shear, axial, torsional loadings. The shear center is assumed to coincide with the neutral axis [5.1].



a. Element Coordinate System b. Element Force and Sign Convention

Figure 5.3 Beam element

The beam element has the following modeling features and limitations

a. The area properties are constant. Therefore, it can not represent the tapered element.

b. Stress can be recovered at four points on the cross section on each end. Those points are determined by the width, height, and thickness.

As Figure 5.3a indicates that six degrees of freedom are present at each node and each element has 12 degrees of freedom resulting in a 12 x 12 elements stiffness matrix. Two reference planes are defined by the orientation vector *v* which can be drawn from GID1 to GID0. GID0 is at (1, 1, 0) in the element coordinate system. The first reference plane 1 is defined by the x-axis and vector *v*. The element coordinate system coincides with the global coordinate system. The beam neutral axis is assumed to be on the x-axis.

The internal forces in beam elements are: the bending moments at each end for each reference plane, M_{1a}, M_{1b}, M_{2a}, and M_{2b}; the shear forces, V_{1a}, V_{2a}, V_{1b}, and V_{2b}; the average axial force, F_{xa}, F_{xb}; and the torque, T_a, T_b. These forces and their sign conventions are illustrated in Figure 5.3b.

When using a single design variable for the bar element such as the thickness, there is a fixed relationship between the design variable (thickness, *t*) and moments of inertia of the element.

$$I_1 = \frac{(h_i + 2t)\cdot(b_i + 2t)^3}{12} - \frac{h_i b_i^{\,3}}{12}$$

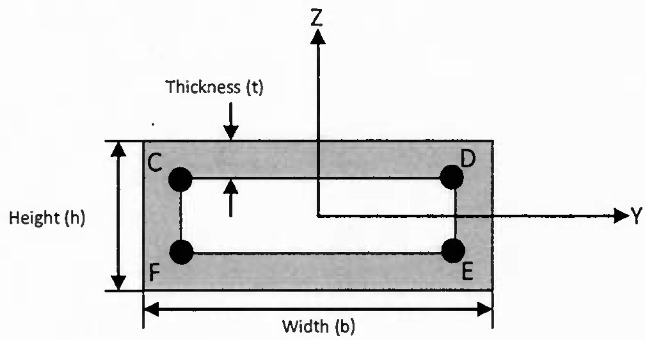
$$I_2 = \frac{(b_i + 2t)\cdot(h_i + 2t)^3}{12} - \frac{b_i h_i^{\,3}}{12} \tag{5.2}$$

$$I_3(=J) = \frac{2t^2(b_i + t)^2(h_i + t)^2}{b_i t + h_i t + 2t^2}$$

Implementation of the relationships dictates that the total element stiffness matrix is made up of a term that is linear in the cross sectional area and a second term that is linear in the moment of inertia and polar moment of inertia:

$$K_e = A \cdot K_e^E + I \cdot K_e^R \tag{5.3}$$

where the E and R superscripts refer to extensional (axial) and rotational (bending and torsional) stiffness terms, respectively.



$$b = b_i + 2t \qquad I_2 = \frac{bh^3}{12} - \frac{b_i h_i^{\,3}}{12}$$

$$h = h_i + 2t \qquad J = \frac{2t^2 (b-t)^2 (h-t)^2}{bt + ht - 2t^2}$$

$$A = bh - b_i h_i \qquad K_1 = \frac{h_i t}{A} \cdot 2$$

$$I_1 = \frac{hb^3}{12} - \frac{h_i b_i^{\,3}}{12} \qquad K_2 = \frac{b_i t}{A} \cdot 2$$

A is the area of bar cross section

J is the torsional constant

I_1 is the area moment of inertia for the bending about Z axis

I_2 is the area moment of inertia for the bending about Y axis

K_1 is the area factor for shear

K_2 is the area factor for shear

Figure 5.4 Beam element cross section and property computation

Figure 5.4 shows beam properties for the finite element model of the beam. Considering the shear deformation, the total transverse deflection is

$$w = w_b + w_s$$
$$\frac{dw_s}{dx} = -\frac{V}{GA_s} \tag{5.4}$$

Where G is shear modulus and A_s is the beam cross sectional area effective in shear. The w_b and w_s are transverse deflections due to bending and shear load respectively. This beam is called Timoshenko beam. The element stiffness matrix is derived as following [5.1].

$$K_{12\times12} = \left[\begin{array}{c|c} K_{11} & K_{12} \\ \hline K_{21} & K_{22} \end{array}\right]_{12\times12} \tag{5.5}$$

$$K_{11} = K_{22} = \begin{bmatrix} \frac{EA}{L} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{12EI_z}{L^3\alpha_y} & 0 & 0 & 0 & \frac{6EI_z}{L^2\alpha_y} \\ 0 & 0 & \frac{12EI_y}{L^3\alpha_z} & 0 & -\frac{6EI_y}{L^2\alpha_z} & 0 \\ 0 & 0 & 0 & \frac{GJ}{L} & 0 & 0 \\ 0 & 0 & -\frac{6EI_y}{L^2\alpha_z} & 0 & \frac{\beta_z EI_y}{L\alpha_z} & 0 \\ 0 & \frac{6EI_z}{L^2\alpha_y} & 0 & 0 & 0 & \frac{\beta_z EI_z}{L\alpha_y} \end{bmatrix} \tag{5.6}$$

$$K_{12} = K_{21}{}^{T} = \begin{bmatrix} -\frac{EA}{L} & 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{12EI_z}{L^3\alpha_y} & 0 & 0 & 0 & -\frac{6EI_z}{L^2\alpha_y} \\ 0 & 0 & -\frac{12EI_y}{L^3\alpha_z} & 0 & \frac{6EI_y}{L^2\alpha_z} & 0 \\ 0 & 0 & 0 & -\frac{GJ}{L} & 0 & 0 \\ 0 & 0 & -\frac{6EI_y}{L^2\alpha_z} & 0 & \frac{\gamma_z EI_y}{L\alpha_z} & 0 \\ 0 & \frac{6EI_z}{L^2\alpha_y} & 0 & 0 & 0 & \frac{\gamma_z EI_z}{L\alpha_y} \end{bmatrix} \tag{5.7}$$

where $\alpha_y = (1+\Phi_y)$, $\alpha_z = (1+\Phi_z)$, $\beta_y = (4+\Phi_y)$, $\beta_z = (4+\Phi_z)$

$$\Phi_y = \frac{12EI_z}{GA_{s_y}L^2},\ \Phi_z = \frac{12EI_y}{GA_{s_z}L^2},\ \gamma_y = (2-\Phi_y),\ \gamma_z = (2-\Phi_z)$$

For the FSD process, the area factor for shear cannot be considered because if the shear stress is taken into account the nonlinearity of the stiffness matrix with respect to the moment of inertia is brought up. In the FSD, the stress ratio is assumed to be proportional to the ratio of the moment of inertia. The shear deformation, thus, is neglected. Therefore the Timoshenko beam is not used here. If the shear deformation is not considered, the beam is referred to as Euler beam and the element stiffness matrix is computed as follows.

$$K_{12\times12} = \left[\begin{array}{c|c} K_{11} & K_{12} \\ \hline K_{21} & K_{22} \end{array}\right]_{12\times12} \tag{5.8}$$

$$K_{11} = K_{22} = \begin{bmatrix} \frac{EA}{L} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{12EI_z}{L^3} & 0 & 0 & 0 & \frac{6EI_z}{L^2} \\ 0 & 0 & \frac{12EI_y}{L^3} & 0 & -\frac{6EI_y}{L^2} & 0 \\ 0 & 0 & 0 & \frac{GJ}{L} & 0 & 0 \\ 0 & 0 & -\frac{6EI_y}{L^2} & 0 & \frac{4EI_y}{L} & 0 \\ 0 & \frac{6EI_z}{L^2} & 0 & 0 & 0 & \frac{4EI_z}{L} \end{bmatrix} \tag{5.9}$$

$$K_{12} = K_{21}{}^T = \begin{bmatrix} -\frac{EA}{L} & 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{12EI_z}{L^3} & 0 & 0 & 0 & -\frac{6EI_z}{L^2} \\ 0 & 0 & -\frac{12EI_y}{L^3} & 0 & \frac{6EI_y}{L^2} & 0 \\ 0 & 0 & 0 & -\frac{GJ}{L} & 0 & 0 \\ 0 & 0 & -\frac{6EI_y}{L^2} & 0 & \frac{2EI_y}{L} & 0 \\ 0 & \frac{6EI_z}{L^2} & 0 & 0 & 0 & \frac{2EI_z}{L} \end{bmatrix} \tag{5.10}$$

The mass matrix is composed with the given lumped mass which includes all the structural and non-structural masses of the whole aircraft. It is not a consistent mass matrix so that there are not off-diagonal terms. The rotary inertia is neglected as a result of simplification by lumping those non/structural masses. The following matrix is used for the element mass matrix.

$$M_{12\times12} = \left[\begin{array}{c|c} M_{11} & 0 \\ \hline 0 & M_{22} \end{array}\right]_{12\times12}$$

$$M_{11_{6\times6}} = \begin{bmatrix} M^{i}_{init} + \Delta M & 0 & 0 & 0 & 0 & 0 \\ 0 & M^{i}_{init} + \Delta M & 0 & 0 & 0 & 0 \\ 0 & 0 & M^{i}_{init} + \Delta M & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$M_{22_{6\times6}} = \begin{bmatrix} M^{i+1}_{init} + \Delta M & 0 & 0 & 0 & 0 & 0 \\ 0 & M^{i+1}_{init} + \Delta M & 0 & 0 & 0 & 0 \\ 0 & 0 & M^{i+1}_{init} + \Delta M & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad (5.11)$$

$$\Delta M = 0.5 \cdot \{(2 \cdot t^{i}_{new} + w^{i}) \cdot (2 \cdot t^{i}_{new} + h^{i}) - (2 \cdot t_{init} + w^{i}) \cdot (2 \cdot t_{init} + h^{i})\} \cdot l^{i} \cdot \rho \qquad (5.12)$$

ΔM	is the mass adjustment
M^{i}_{init}	is the lumped initial mass
t^{i}_{new}	is the new design variable of i^{th} element
h^{i}	is the height
w^{i}	is the width
l^{i}	is the length
ρ	Is the structure material density

ΔM is computed after FSD. FSD computes the optimal thickness which is resulting in the change of the mass. This computation is repeating until convergence.

5.2 Fully Stressed Design (FSD) Algorithm

While FSD methods are, by definition, severely limited in scope, this method is chosen because of the rapidity in achieving a feasible strength design. The implementation of FSD recognizes the inherent limitations of this method, so the FSD is intended to be used as a preliminary step to achieve a feasible or near optimal strength design. It is, of course, useful for problems in which only stress constraints for static disciplines are applied.

The FSD resizing is for problems where static strength constraints play an important role in determining the structural sizes and the FSD can find a reasonable initial design very quickly. Therefore, while the FSD method itself can treat only the static stress constraints, the FSD may be used in almost any optimization problem where stress constraints are applied. Since the determination of an initial design is the typical purpose for FSD, the algorithm has been implemented in such a way that the user selects some number of initial design cycles to be performed using FSD.

In the implementation of the FSD resizing concept, the new local design variable (which represents the physical property of one finite element; e.g., the area of cross section) is found based on the ratio of stress to the allowable stress [5.2]:

$$t_{i_{new}} = \max\left[\left(\frac{\sigma}{\sigma_{allowable}}\right)_i^{\alpha} t_{i_{old}}, t_{i_{\min}}\right] \tag{5.13}$$

The stress ratio is determined from the applied maximum stress and safety factor constraints. The only difficulty in performing this operation is in the bookkeeping to determine which stress constraint corresponds to a particular local design variable. More important is the treatment of stress constraints applied to un-designed elements for which there is no corresponding local variable. Since the implementation of this method is intended to be approximate, it is decided to ignore these stress constraints in the computation of the new local design variable vector. This is consistent with the fact that all the other constraint types are also ignored.

To offer an improved convergence behavior for this FSD algorithm, the exponential factor, α, has been provided in Equation (5.13). Small values of α result in the better convergence at the expense of additional iterations. The value of this parameter is user selectable in the alpha field in BEAMFSD card, but defaults to 0.90. This value was chosen for its rapid movement toward a fully stressed design in the initial iterations. If FSD is intended to be used to achieve a final converged solution, a value of 0.50 or less is preferred. In this module, the design variable is not directly updated in the FSD module but rather the moment of inertia is updated as the Equation (5.14).

$$I_i = \max\left[\left(\frac{\sigma_i}{\sigma_{allowable}}\right)^{\alpha} I_{i-1}, I_{\min}\right] \tag{5.14}$$

Where it assumed to be converged if $|I_i - I_{i-1}| < chkcon1$ and it iterates until the convergence. $I_{\min}$ is computed from the minimum design variable value. The $chkcon1$ is given by the user inputs in the BEAMFSD card. If the structure is statically deterministic one iteration of analysis and $\alpha = 1$ are enough condition to get the final design. However the statically in deterministic system requires iterations because of the compatibility. The design variable is updated in the current element by FSD algorithm and then the whole structure's response is changed due to the variation of the design variable. This makes the different stress in the adjacent elements. However the stress value for the adjacent elements under consideration is from the structure before updating the design variable of the element. Therefore it needs iteration until convergence.

In addition, the converged values in each loading condition are compared and the maximum values are chosen to get the final design. This algorithm is shown as Equation (5.15).

$$I_i^j = \max_{k=1,NLC}\left(\max\left[I_{i-1}^j \frac{\sigma_{j,k}}{\sigma_{allowable}}, I_{\min}\right]\right) \tag{5.15}$$

Where I is moment of inertia, superscript j is element number, subscript i is iteration number, k is loading condition, NLC is number of loading condition, $\sigma_{j,k}$ is current element's stress under k^{th} loading condition, and $\sigma_{allowable}$ is allowable stress.

5.3 Inertia Relief

After removing the depending degree of freedoms (DOF) in multi-point constraints (MPC), one can get the n-set DOF. Then the single point constraints (SPC) are eliminated from n-set and the f-set DOF is given. After taking account of the DOF for Guyan reduction, finally the a-set DOF is available. This a-set DOF can be separated into the r and l-sets of DOF and the corresponding equation of motion can be expressed as follows.

$$\begin{bmatrix} M_{rr} & M_{rl} \\ M_{lr} & M_{ll} \end{bmatrix} \begin{Bmatrix} \ddot{u}_r \\ \ddot{u}_l \end{Bmatrix} + \begin{bmatrix} K_{rr} & K_{rl} \\ K_{lr} & K_{ll} \end{bmatrix} \begin{Bmatrix} u_r \\ u_l \end{Bmatrix} = \begin{Bmatrix} F_r \\ F_l \end{Bmatrix} \tag{5.16}$$

The r-set is given by the 6 degree of freedoms from the supported grid point. The given structure under consideration is the free-free supported and there are not either MPC or SPC. The Guyan reduction is not used either so that g-set is same as the a-set in this SMB module. Using rigid-body transformation (Craig-Bampton 1965 [5.3]),

$$\begin{gathered} \begin{Bmatrix} \ddot{u}_r \\ \ddot{u}_l \end{Bmatrix} = \begin{bmatrix} I_{rr} \\ -K_{ll}{}^{-1} K_{lr} \end{bmatrix} \{\ddot{u}_r\} = [\Phi]\{\ddot{u}_r\} \\ \begin{bmatrix} I_{rr} \\ -K_{ll}{}^{-1} K_{lr} \end{bmatrix} = [\Phi] \end{gathered} \tag{5.17}$$

Multiplying both sides in Equation (5.16) by $[\Phi]$.

$$\{0\} = [\Phi]^T \{F\} - [\Phi]^T [M][\Phi]\{\ddot{u}_r\} \tag{5.18}$$

Thus, $\{\ddot{u}_r\}$ is derived from Equation (5.18).

$$\{\ddot{u}_r\} = \left[[\Phi]^T [M][\Phi]\right]^{-1} \cdot [\Phi]^T \cdot \{F\} \tag{5.19}$$

The acceleration vector can be substituted by the Equation (5.19) and then the Equation (5.16) can be rewritten.

$$\begin{bmatrix} K_{rr} & K_{rl} \\ K_{lr} & K_{ll} \end{bmatrix} \begin{Bmatrix} u_r \\ u_l \end{Bmatrix} = \begin{Bmatrix} F_r \\ F_l \end{Bmatrix} - \begin{bmatrix} M_{rr} & M_{rl} \\ M_{lr} & M_{ll} \end{bmatrix} [\Phi]\{\ddot{u}_r\} \tag{5.20}$$

The $\{u_r\}$ can be equal to $\{0\}$ and the Equation (5.19) can be substituted for the $\{\ddot{u}_r\}$ in Equation (5.20) [5.4].

$$[K_{ll}]\{u_l\} = \{F_l\} - [M_{lr} \quad M_{ll}][\Phi]\left[[\Phi]^T [M][\Phi]\right]^{-1} [\Phi]\{F\} \tag{5.21}$$

Thus, the elastic deformation due to the rigid body acceleration is

$$\{u_l\} = [K_{ll}]^{-1}\{F_l\} - [K_{ll}]^{-1}[M_{lr} \quad M_{ll}][\Phi][M_r]^{-1}[\Phi]\{F\} \tag{5.22}$$

Where the $[M_r]$ equal to $[\Phi]^T [M][\Phi]$.

The derived deformed shapes are used to get the stress computation. In this module the supporting point is the first grid point which is (0, 0, 0) in the basic coordinate system.

Chapter 6 Trim Module

The objective of the Trim module is to compute the trim solution with structural flexibility effects and the structural deformation by solving a two-degree nonlinear longitudinal trim problem. This trim problem involves two trim variables, namely, the angle of attack (α) and the control surface deflection angle (δ) whose solutions satisfy the lift-equal-weight and zero-pitch-moment trim conditions. The nonlinearity of the trim problem arises from the fact that the aerodynamics of the hypersonic flight vehicle is nonlinear with respect to the angle of attack and control surface deflection. To solve such a nonlinear trim problem requires a search algorithm that iterates on a linearized two-degree trim equation. This two-degree trim equation involves the linearized aerodynamic stability derivatives as well as the aerodynamic derivatives due to structural deformation at each trim iteration. These aerodynamic derivatives are obtained by applying the Complex Variable Differentiation (CVD) technique to UCDA.

6.1 Generation of Aerodynamic Derivatives by Applying CVD to UCDA

As already discussed in Section 4.6, the CVD technique is a numerically exact differentiation technique and is easy to be implemented. To apply the CVD technique to UCDA is very straightforward, simply converting all real variables in the code to complex variables. However, there are several intrinsic functions such as ATAN, ASIN, and ACOS whose complex counterparts do not exist in the standard FORTRAN. The mathematical expressions of those intrinsic functions are available. However, it is found that directly coding these mathematical expressions into a FORTRAN program leads to incorrect results due to the numerical truncation error if the imaginary part of the input complex value is very small. For instance, the complex version of ATAN is:

$$\mathrm{CATAN}(x+iy)=\frac{1}{2}\mathrm{ATAN}\left(2x,1-x^2-y^2\right)+i\left(\frac{1}{4}\log(a_1)-\frac{1}{4}\log(a_2)\right) \tag{6.1}$$

where $a_1 = x^2 + y^2 + 2y + 1.0$

$a_2 = x^2 + y^2 - 2y + 1.0$

For a very small y, for example $y = 10^{-30}$, the imaginary part of Equation (6.1) becomes computational zero which is obviously incorrect. This is because in the 32-bit computer the function $\log(a_1) - \log(a_2)$ is below machine zero even using double precision computations. To circumvent this problem, we have derived a special case for the complex version of ATAN for very small y. This is done by simply taking the Taylor's expansion of $\mathrm{ATAN}(x+iy)$ for small y which gives,

$$\mathrm{CATAN}(x+iy) = \mathrm{ATAN}(x) + i\frac{y}{\left(1+x^2\right)} \tag{6.2}$$

Since $y \approx 10^{-30}$, the truncation error due to the higher order terms is 10^{-60} which is below machine zero. Thus, Equation (6.2) provides a numerically exact result of the complex function ATAN.

Similar Taylor's expansion can be applied to other intrinsic functions such as ASIN and ACOS.

Typical aerodynamic stability derivatives obtained from the complex version of UCDA are shown in Figures 6.1, 6.2 and 6.3. Figures 6.1 through 6.3 compare the aerodynamic stability derivatives of axial force, lift force and pitching moment respectively with respect to angle of attack, control surface deflection, Mach number and altitude for SEM at a given mean flow condition. Clearly, CVD compares well with Finite Difference (FD) for at least one choice of step size used by FD. This goes to show that for a highly nonlinear flow as prevalent in hypersonic aerodynamics, CVD is a good choice of finding the right derivative because different choices of the difference parameters for independent variables can lead to different derivatives, making FD a non reliable method of evaluating derivates.

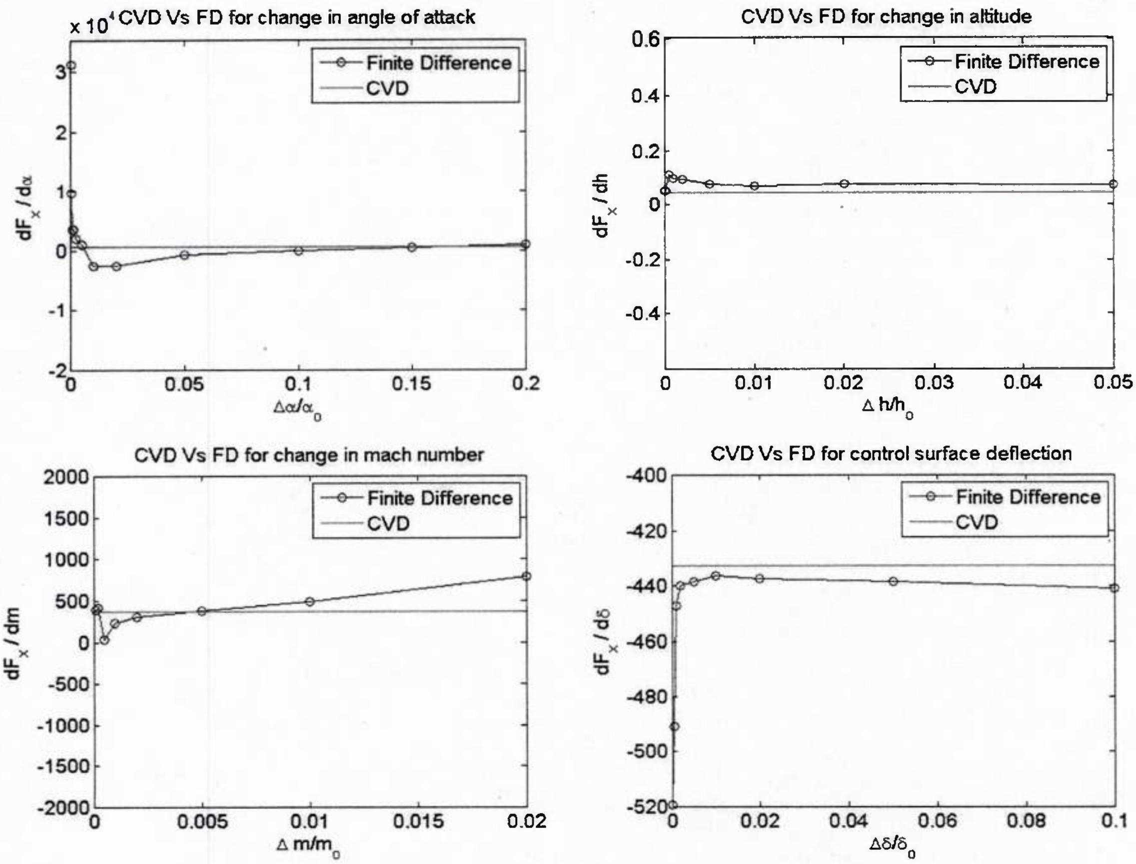
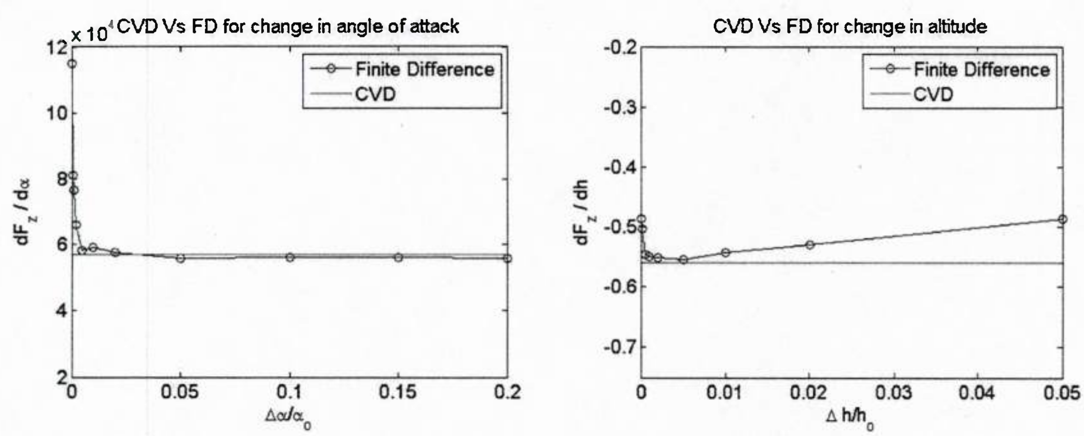


Figure 6.1 Sensitivity of axial force (*Fx*) with respect to angle of attack, altitude, Mach number and control surface deflection



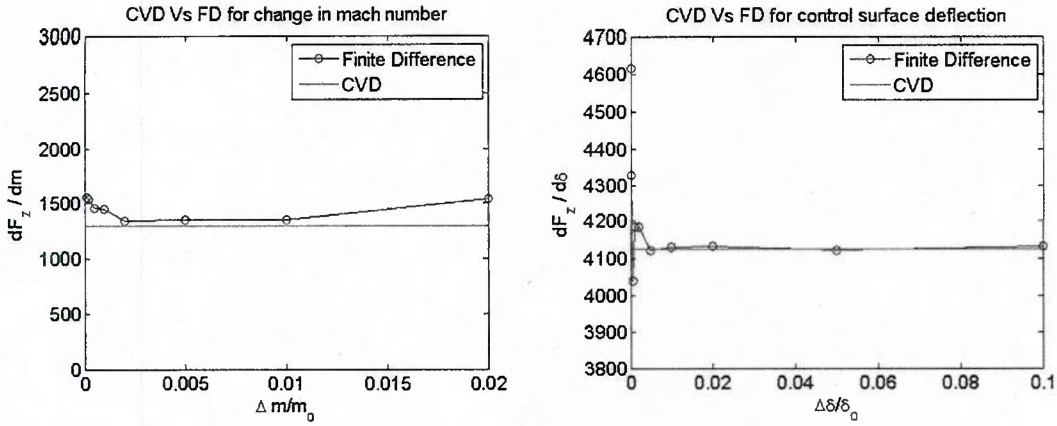


Figure 6.2 Sensitivity of lift force (*Fz*) with respect to angle of attack, altitude, Mach number and control surface deflection

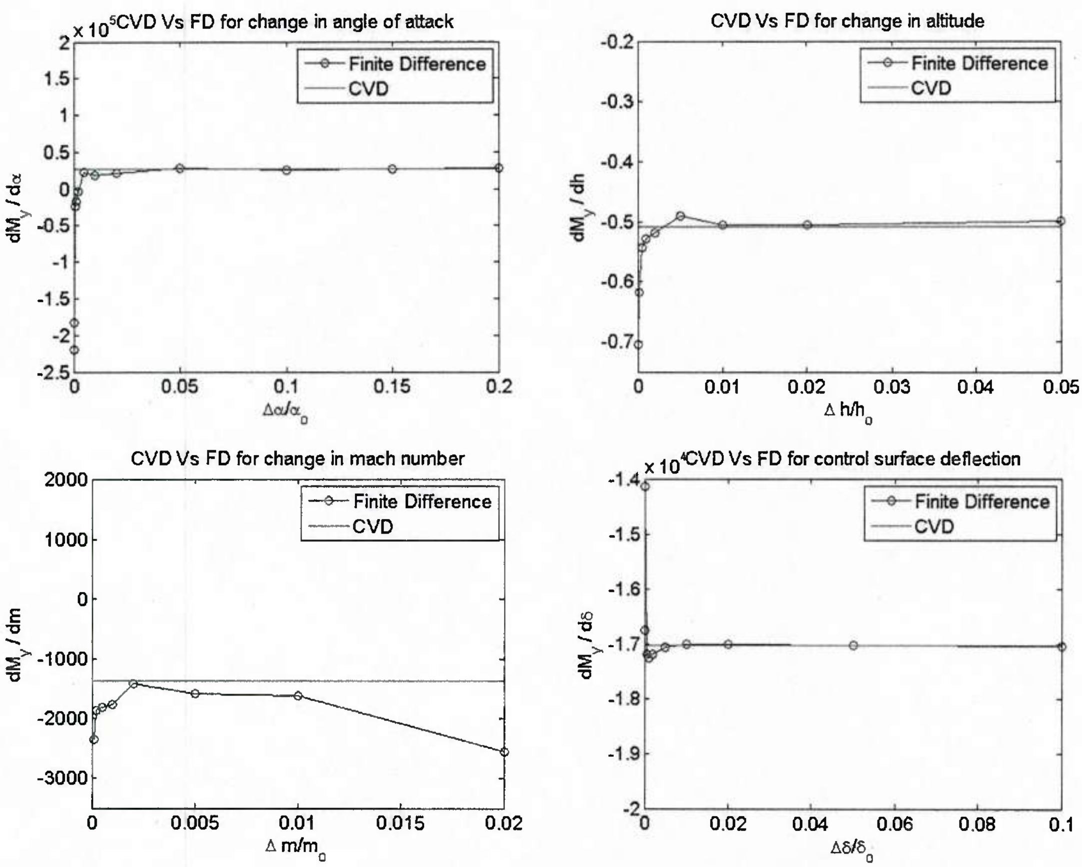


Figure 6.3 Sensitivity of pitching moment (*My*) with respect to angle of attack, altitude, Mach number and control surface deflection

6.2 Derivation of the Linearized Trim Equation

Considering angle of attack (α), control surface deflection (δ) and generalized coordinates (η) of the structural mode shapes as the dependent variables, the total force at a particular mean flow condition expressed as a function of the mean angle of attack (α_0), and the mean control surface deflection angle (δ_0) on a flying vehicle can be summed up as:

$$F_T = F_0(\alpha_0, \delta_0) + F_\alpha(\alpha_0, \delta_0)\alpha + F_\delta(\alpha_0, \delta_0)\delta + F_\eta(\alpha_0, \delta_0)\eta \tag{6.3}$$

where F_T is the total aerodynamic force, F_0 is the aerodynamic force at the mean flow condition, F_α , F_δ and F_η are forces due to small perturbations in angle of attack α, control surface deflection δ and generalized coordinate η. In terms of the deformation of the structure, the force F_T can also be written as:

$$F_T = KX \tag{6.4}$$

where K is the stiffness matrix of the structure and X is the structural deformation.

Assuming the structural deformation can be expressed as a superposition of the mode shapes, the structure deformation can be written as:

$$X = \phi_\eta \eta \tag{6.5}$$

where ϕ_η is the mode shape corresponding to each generalized coordinate.

Pre-multiplying ϕ_n^T with Equation (6.4) and using Equation (6.3), we arrive at:

$$\left[\phi_\eta^T K \phi_\eta\right]\eta = \phi_\eta^T F_T = \phi_\eta^T F_0 + \phi_\eta^T F_\alpha \alpha + \phi_\eta^T F_\delta \delta + \phi_\eta^T F_\eta \eta \tag{6.6}$$

The generalized stiffness can be defined as

$$K_\eta = \phi_\eta^T K \phi_\eta = \omega_\eta^2 m_\eta \tag{6.7}$$

where ω_η and m_η are natural frequencies and generalized mass matrix, respectively. Note that ϕ_η, ω_η and m_η are provided by the SMB module.

Combining Equation (6.6) and Equation (6.7), we get:

$$\left[K_\eta - \phi_\eta^T F_\eta\right]\eta = \phi_\eta^T F_0 + \phi_\eta^T F_\alpha \alpha + \phi_\eta^T F_\delta \delta \tag{6.8}$$

Now if we consider,

$$K_{ae} = \left[K_\eta - \phi_\eta^T F_\eta\right] \tag{6.9}$$

Then,

$$\eta = K_{ae}^{-1}\left[\phi_\eta^T F_0 + \phi_\eta^T F_\alpha \alpha + \phi_\eta^T F_\delta \delta\right] \tag{6.10}$$

Putting Equation (6.10) in Equation (6.3), we have,

$$F_T = F_0 + F_\alpha \alpha + F_\delta \delta + F_\eta K_{ae}^{-1}\phi_\eta^T F_0 + F_\eta K_{ae}^{-1}\phi_\eta^T F_\alpha \alpha + F_\eta K_{ae}^{-1}\phi_\eta^T F_\delta \delta \tag{6.11}$$

Equation (6.11) can be rewritten as,

$$F_T = [I + A]F_0 + [I + A]F_\alpha \alpha + [I + A]F_\delta \delta \tag{6.12}$$

where

$$A = F_\eta K_{ae}^{-1}\phi_\eta^T \tag{6.13}$$

Now, for trim condition, we satisfy two equations:

$$L = \phi_Z^T F_T = \eta_Z W \tag{6.14}$$

and

$$M = \phi_R^T F_T = 0 \tag{6.15}$$

where L is lift, M is pitching moment about the center of gravity (C.G.), W is weight of the vehicle, ϕ_Z^T is unit vector along the direction of the lift, ϕ_R^T is a vector containing pitching moment arm and η_Z is the load factor. For a level flight, $\eta_Z = 1$.

Using Equation (6.12), we finally arrive at the following 2 X 2 linearized trim equations:

$$\begin{bmatrix} \phi_Z^T [I+A] F_\alpha & \phi_Z^T [I+A] F_\delta \\ \phi_R^T [I+A] F_\alpha & \phi_R^T [I+A] F_\delta \end{bmatrix} \begin{Bmatrix} \alpha \\ \delta \end{Bmatrix} = \begin{bmatrix} \eta_Z W - \phi_Z^T A F_0 \\ -\phi_R^T A F_0 \end{bmatrix} \tag{6.16}$$

6.3 Trim Iterations for the Nonlinear Trim Problem

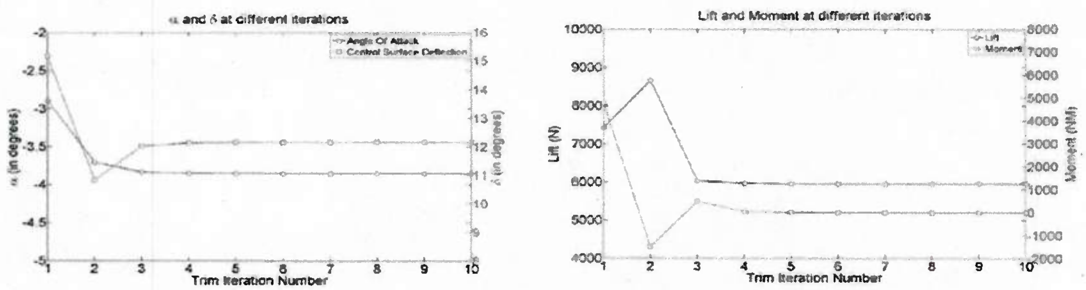
All aerodynamic derivatives involved in Equation (6.16) can be considered as the gradient of the trim variables at the current mean flow condition. The trim solution can be immediately calculated by adding the trim variable solutions (α and δ) to their respective mean flow conditions (α_0 and δ_0) if the aerodynamics and propulsion are linearly varying with respect to the trim variable, i.e. the gradient of the trim variable is constant. However, in hypersonic flow, not only are these aerodynamic derivatives known to be nonlinear but also the propulsion strongly depend on the mean flow condition. Therefore, to reach a final trim solution that satisfies the lift-equal-weight and zero-pitch-moment conditions requires an iterative process. In

this iterative process, the solution of the trim variables is added to the current mean flow condition to serve as a new mean flow condition for the next trim iteration such as:

$$\begin{aligned} \alpha_{0_{new}} &= \alpha_{0_{old}} + \alpha \\ \delta_{0_{new}} &= \delta_{0_{old}} + \delta \end{aligned} \tag{6.17}$$

At the new mean flow condition, the complex version of UCDA is executed again to generate a new set of aerodynamic forces and the stability derivatives that are plugged into Equation (6.16) to solve for the trim variables. This process is repeated until the change of the mean flow condition between two consecutive iteration steps is sufficiently small.

A typical iteration history of such an iterative process is shown in Figure 6.4. It can be seen that this iterative process requires only less than 10 iterations to achieve a fully converged solution. In fact, the mean flow condition in terms of α_0 and δ_0 does not change significantly after 5 iterations. Meanwhile, the lift and moment at the fifth iteration have already nearly satisfied the lift-equal-weight and zero-pitch-moment conditions. From the fifth to the tenth iteration, the trim solution remains nearly the same; indicating that this iterative process is stable and provides a fast converging rate.



(a) Mean Flow Condition (b) Lift and Pitch Moment

Figure 6.4 Iteration history of the iterative process for solving the nonlinear trim problem

Chapter 7 AeroServoElasticity (ASE) Module

Because of the waverider-like design, the forebody of the scramjet flight vehicle normally produces a large amount of lift when compared to the rest of the vehicle and consequently creates a large pitch-up moment. This implies that, most likely, the waverider design is statically unstable. This probably was the reason why NASA's Hyper-X, Mach 7 configuration required a 1000 pound block of tungsten in the forebody to balance the pitch-up moment. Apparently, this 1000 pound block of tungsten gives a large weight penalty to the NASA's Hyper-X configuration and significantly reduces its performance. Thus, the stability and controllability of the scramjet design must be analyzed in the early design stage. In addition, the structural flexibility and unsteady aerodynamic effects may have a large impact on the stability and must be included in the analysis. All of these call for an aeroservoelastic (ASE) capability that can analyze the coupling mechanism among the aerodynamics, structure and control system. It is for this reason that we have developed an ASE module as an integral part of the ASTPE system.

The functionality of the ASE module is two-fold. First, it calculates the longitudinal stability of the flight dynamics system with structural flexibility and unsteady aerodynamic effects. Then, it generates a state-space equation of the plant that can be directly adopted by MATLAB for a flight control system design.

The ASE module operates on the complex version of UCDA to obtain the aerodynamic stability derivatives for the construction of the state-space equation. However, since UCDA produces only the steady aerodynamics, we have incorporated a Local Pulsating Cone Method [7.1] in UCDA to compute the unsteady aerodynamics and the aerodynamic damping derivatives. Furthermore, in addition to the aerodynamic stability derivatives of angle of attack and control surface, these of the pitch rate (q) and forward velocity (u) are also developed in UCDA. Finally, the ASE module generates a state-space equation of the plant using a unified aeroelastic and flight dynamic formulation described in reference [7.2].

7.1 The Local Pulsating Cone (LPC) Method for Unsteady Aerodynamics

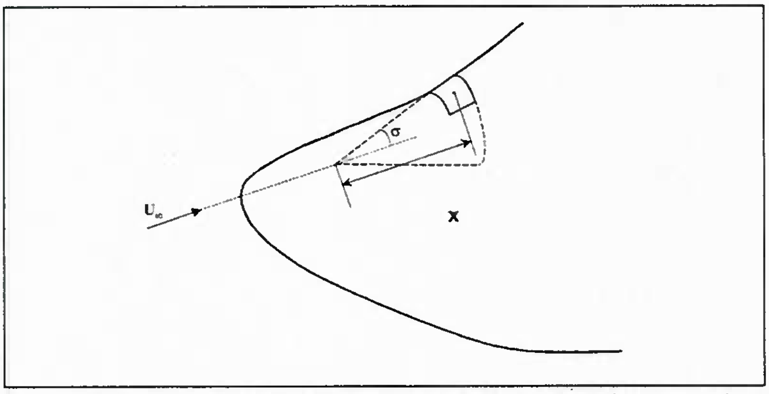


Figure 7.1 Local pulsating cone analogy showing rotations

Since the mean flow is hypersonic / supersonic, the time required for it to travel a unit reference length L (say body length) is much faster than that required for one cycle of body oscillation. Therefore, the corresponding unsteady problem can be treated as mildly unsteady in that flow history is only accounted for in the neighborhood of each panel. Thus, considered a panel located on a body such as the one shown in Figure 7.1, the real part (ΔC_{P_R}) and the imaginary part (ΔC_{P_I}) of the unsteady pressure coefficient on this panel can be approximated as:

$$\Delta C_{P_R} = \left(\frac{dC_{P_R}}{d\delta}\right)_{\sigma} \cos\theta$$

$$\Delta C_{P_I} = \left(\frac{dC_{P_I}}{d\delta}\right)_{\sigma} \bar{x}\, \cos\theta \tag{7.1}$$

where:

θ is the azimuthal angle and σ is the semi-angle of the local cone (Figure 7.1)

$\bar{x}$ is the axial distance between the panel and the local cone apex (Figure 7.1)

$\left(\frac{dC_{P_R}}{d\delta}\right)_{\sigma}$ and $\left(\frac{dC_{P_I}}{d\delta}\right)_{\sigma}$ are respectively the in-phase and out-of-phase pressure coefficients of the local cone undergoing a unit pulsating motion.

In fact, they can be related by the normal force derivatives in pitch, i.e.:

$$\Delta C_{N_\alpha} = \frac{1}{\pi \tan^2\sigma} \int_0^1 \int_0^{2\pi} \left(\frac{dC_{P_R}}{d\delta} \right)_\sigma r \left(\cos^2\theta\right) d\theta \, d\bar{x}$$
$$= \frac{1}{2\tan\sigma} \left(\frac{dC_{P_R}}{d\delta} \right)_\sigma$$

$$\Delta C_{N_q} = \frac{1}{\pi \tan^2\sigma} \int_0^1 \int_0^{2\pi} \left(\frac{dC_{P_I}}{d\delta} \right)_\sigma \bar{x}\, r \left(\cos^2\theta\right) d\theta \, d\bar{x}$$
$$= \frac{1}{3\tan\sigma} \left(\frac{dC_{P_I}}{d\delta} \right)_\sigma \tag{7.2}$$

where ΔC_{N_α} and ΔC_{N_q} are respectively the stiffness and pitch-damping derivatives of the local cone. The exact Euler values of C_{N_α} and C_{N_q} for an oscillating cone were given by Sims [7.3] and Brong [7.4]. Once the real part (ΔC_{P_R}) and the imaginary part (ΔC_{P_I}) are obtained, they can be integrated to generate the static and dynamic aerodynamic stability derivatives due to a given unsteady motion. The accuracy of the Local Pulsating Cone Method has been validated with many other methods and wind-tunnel data.

The coefficients of out-of-phase forces with varying Mach numbers for a pitching 10° cone and a 20° cone about the apex are presented respectively in Figures 7.2 and 7.3. It is seen that the Local Pulsating Cone (LPC) results largely follow the same trend as Brong's Exact Euler solutions [7.4], but with acceptable discrepancy, throughout the Mach number range from shock detachment to $M_\infty = 20$. Much larger discrepancies were found between results of Tobak-Wehrend's first order theory [7.5] and that of Brong's Exact Euler solution. McIntosh's numerical solution [7.6] agrees very well with Brong's Exact Euler Solution at high Mach numbers, but it yields large discrepancies at low supersonic Mach numbers.

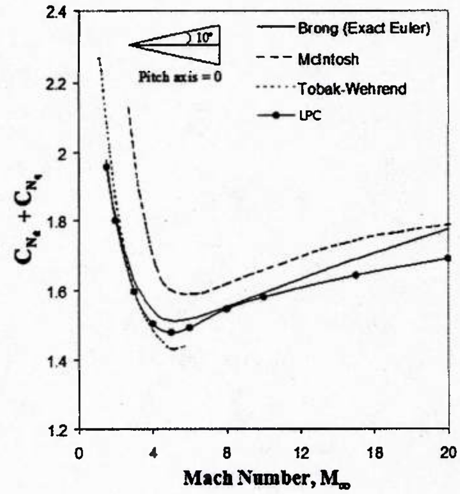


Figure 7.2 Variation with Mach number of the stability derivative (at cone angle = 10°)

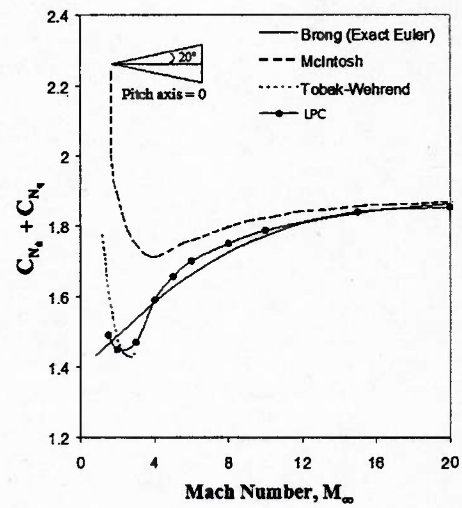


Figure 7.3 Variation with Mach number of the stability derivative (at cone angle = 20°)

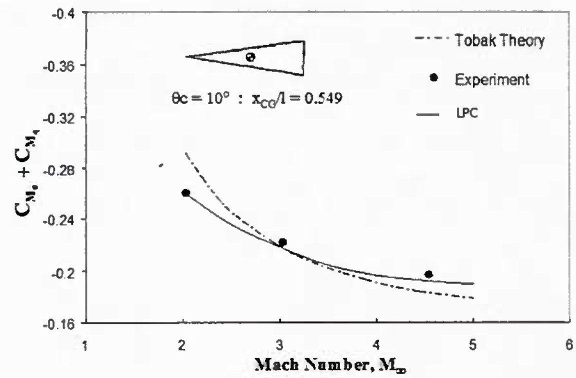


Figure 7.4 Predicted and measured damping of a 10-deg sharp cone

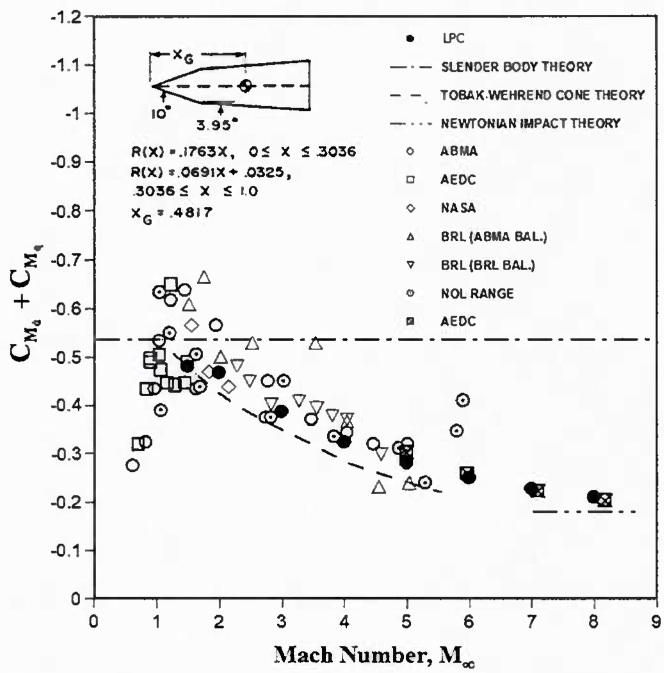


Figure 7.5 Comparison of theoretical and experimental damping-in-pitch moment coefficients for a cone frustum at various Mach numbers

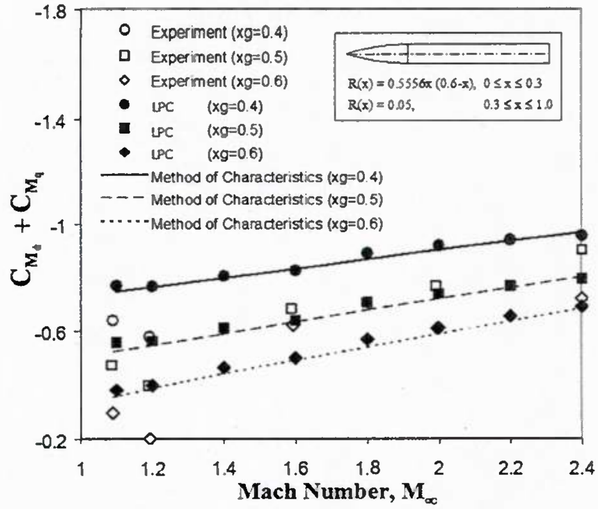


Figure 7.6 Effect of Mach number on fixed axis damping in pitch moment coefficient for an Ogive cylinder

Figures 7.4, 7.5 and 7.6 compare respectively the pitch-damping results computed by the Local Pulsating Cone Method with the measure data for an oscillating 10° cone frustum and for a slender ogive-cylinder body at various range of moderate supersonic Mach numbers. Excellent agreements were found for all cases considered.

7.2 The Unified Aeroelastic and Flight Dynamic Formulation for the State-Space Equation Generation

The unified aeroelastic and flight dynamic formulation described in Reference [7.2] starts from the state-space equation based on the structural generalized coordinates including the rigid body and elastic modes. For longitudinal dynamics, there are three rigid body modes, namely T_x for fore-aft mode, T_z for plunge mode and R_y for pitch mode and a set of generalized coordinates (η) of the elastic mode. Thus the deformation vector {X} can be expressed as

$$\{X\} = \left[\phi_x \phi_z \phi_\theta \phi_\eta\right] \begin{bmatrix} T_x \\ T_z \\ R_y \\ \eta \end{bmatrix} \tag{7.3}$$

Where ϕ_x is the fore-aft mode, ϕ_z is the plunge mode, ϕ_θ is the pitch mode and ϕ_η are the elastic modes. Introduce a state vector:

$$\{x_{a e}\}^T = \{T_x T_z R_y \eta \dot{T}_x \dot{T}_z \dot{R}_y \dot{\eta}\} \tag{7.4}$$

The state space equation of the aeroelastic model can be expressed as:

$$\{\dot{X}_{ae}\} = [A]\{X_{ae}\} + [B]\{\delta\} \tag{7.5}$$

where

$$[A] = \begin{bmatrix} 0_{4x4} & I_{4x4} \\ -M^{-1}\left[K + q_\infty A_{s0}\right]_{4x4} & -M^{-1}\left[C + \frac{q_\infty}{V_\infty} A_{s1}\right]_{4x4} \end{bmatrix} \tag{7.6}$$

$$[B] = \begin{bmatrix} 0_{4xn_c} \\ -q_\infty [M]^{-1} [A_{c0}] 4xn_c \end{bmatrix} \tag{7.7}$$

where

c is the reference chord and S is the reference area

q_∞ is the dynamic pressure

V_∞ is the freestream velocity

n_c is the number of control inputs

and *M*, *K*, and *C* are the generalized mass, stiffness and damping matrices, respectively, and are expressed as:

$$M = \begin{bmatrix} m & 0 & 0 & 0 \\ 0 & m & 0 & 0 \\ 0 & 0 & I_{yy} & 0 \\ 0 & 0 & 0 & m_\eta \end{bmatrix} \tag{7.8}$$

$$K = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \omega_\eta^2 m_\eta \end{bmatrix} \tag{7.9}$$

$$C = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2m_\eta \omega_\eta \zeta \end{bmatrix} \tag{7.10}$$

where

m is the mass of the vehicle.

I_{yy} is the moment of inertia about Y axis.

m_η are the generalized masses of the elastic modes.

ω_η are the natural frequencies of the elastic modes and,

ζ are the damping ratio of the elastic modes.

A_{s0} contains the static aerodynamic stability derivatives of the angle of attack and the elastic modes:

$$\left[A_{s0}\right]_{sym} = \begin{bmatrix} 0 & 0 & -S\left(C_{D_\alpha} - C_{L_0}\right) - {}^{mg}/_{q_\infty} & -C_{D_\eta} S \\ 0 & 0 & -S\left(C_{L_\alpha} + C_{D0}\right) & -C_{L_\eta} S \\ 0 & 0 & -ScC_{m_\alpha} & -C_{M_\eta} Sc \\ 0 & 0 & -\phi_\eta^T \, {}^{F_\alpha}/_{q_\infty} & -\phi_\eta^T \, {}^{F_\eta}/_{q_\infty} \end{bmatrix} \tag{7.11}$$

where

F_α is the distributed aerodynamic force due to angle of attack.

F_η is the distributed aerodynamic force due to the elastic modes, and

$C_{D\eta}$, $C_{L\eta}$, $C_{M\eta}$ are the non-dimensional drag, lift and pitch moment coefficients due to the elastic modes

It should be note that in Equation (7.11) the weight of the vehicle (mg) is also included. This is an essential term to obtain the correct phugoid mode.

A_{s1} contains the aerodynamic damping derivatives of the forward velocity (u), the angle of attack (α), the pitch rate (q) and the elastic modes (η):

$$\left[A_{S1}\right]_{sym} = \begin{bmatrix} 2S\left(C_{D_u}+C_{D_0}\right) & S\left(C_{D_\alpha}-C_{L_0}\right) & -0.5S\,c\left(C_{D_{\dot\alpha}}+C_{D_q}\right) & -C_{D_{\dot\eta}}S \\ 2S\left(C_{L_u}+C_{L_0}\right) & S\left(C_{L_\alpha}+C_{D_0}\right) & -0.5S\,c\left(C_{L_{\dot\alpha}}+C_{L_q}\right) & -C_{L_{\dot\eta}}S \\ 2Sc\left(C_{M_u}+C_{M_0}\right) & ScC_{M_\alpha} & -0.5Sc^2\left(C_{M_{\dot\alpha}}+C_{M_q}\right) & -C_{M_{\dot\eta}}Sc \\ 2\phi_\eta^T\dfrac{\left[F_u+F_0\right]}{q_\infty} & \phi_\eta^T\dfrac{\left[F_\alpha\right]}{q_\infty} & -0.5c\phi_\eta^T\dfrac{\left[F_q\right]}{q_\infty} & -\phi_\eta^T\dfrac{F_{\dot\eta}}{q_\infty} \end{bmatrix} \tag{7.12}$$

where

F_u is the distributed aerodynamic force due to unit change in forward speed (u).

F_0 is the distributed aerodynamic force at trim.

F_q is the distributed aerodynamic force due to the pitch rate (q).

$F_{\dot\eta}$ is the distributed aerodynamic force due to $\dot\eta$.

Note that $F_{\dot\eta}$ is obtained by applying the Local Pulsating Cone method described in Section 7.1, and $C_{D_{\dot\eta}}$, $C_{L_{\dot\eta}}$, $C_{M_{\dot\eta}}$ are the drag, lift and pitch moment due to the rate of the elastic modes ($\dot\eta$). They are computed by integrating $F_{\dot\eta}$ over the surface mesh.

A_{c0} contains the aerodynamic stability derivatives of the control surfaces:

$$[A_{c0}]_{sym} = \begin{bmatrix} -SC_{D_\delta} \\ -SC_{L_\delta} \\ -cSC_{M_\delta} \\ -\phi_\eta^T F_\delta / q_\infty \end{bmatrix} \tag{7.13}$$

F_δ is the distributed aerodynamic forces due to unit change of control surface deflection δ.

The state vector shown in Equation (7.4) is expressed in terms of the structural rigid body modes and the elastic modes. However, the states of the flight dynamic model are expressed in terms of the airframe states. To be compatible with the flight dynamic model, it is required to transform the rigid body modes to the airframe states. This transformation matrix for the longitudinal dynamics is shown in the following equation:

$$\{X_{ae}\} = [T_A]\{\xi\} \tag{7.14}$$

Where $\{\xi\}$ is the airframe states expressed as:

$$\{\xi\} = \begin{bmatrix} x & u & h & \alpha & \theta & q & \eta & \dot{\eta} \end{bmatrix}^T \tag{7.15}$$

and

$$[T_A] = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -V_\infty & V_\infty & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{7.16}$$

Substituting Equation (7.16) in to Equation (7.5) yields a state-space equation defined in the airframe states:

$$\left\{\dot{\xi}\right\} = \left[\bar{A}\right]\{\xi\} + \left[\bar{B}\right]\{\delta\} \tag{7.17}$$

where

$$\left[\bar{A}\right] = [T_A]^{-1}[A][T_A] \tag{7.18}$$

and

$$\left[\bar{B}\right] = [T_A]^{-1}[B] \tag{7.19}$$

The stability of the flight dynamic system with aeroelastic effects can be computed by performing an eigenvalue analysis of the matrix $\left[\bar{A}\right]$. This state-space equation can then be imported into MATLAB for a subsequent flight control law design.

7.3 Validation of the ASE module

The validation of the ASE module can be achieved by first excluding the elastic modes then comparing the eigenvalues of the matrix $\left[\bar{A}\right]$ to those of analytical flight dynamic equations such as those in Reference [7.7] and shown in the following equations:

For Phugoid mode:

$$\omega_{np} = \frac{\rho S U \sqrt{-C_{L_u} C_{L_o}}}{2m} \tag{7.20}$$

$$\zeta_p = \frac{-C_{x_u}}{2\dfrac{mU}{Sq}\dfrac{\sqrt{-C_{L_u} C_L}}{mU/Sq}} = \frac{-C_{D_u}}{2\sqrt{-C_{L_u} C_{L_o}}} \tag{7.21}$$

For short period mode:

$$\omega = \left(\frac{\frac{c}{2U} C_{m_q} C_{L_\alpha} - \frac{mU}{Sq} C_{m_\alpha}}{\left(\frac{I_y}{Sqc}\right)\left(\frac{mU}{Sq}\right)} \right)^{1/2} \tag{7.22}$$

$$\zeta = -\frac{1}{4}\left(C_{m_q} + C_{m_\alpha} + \frac{2I_y}{mc^2} C_{L_\alpha} \right) \left(\frac{mc^2}{I_y \left(\frac{C_{m_q} C_{L_\alpha}}{2} - \frac{2mC_{m_\alpha}}{pSc} \right)} \right)^{1/2} \tag{7.23}$$

The aerodynamic stability derivatives are computed first on the selected scramjet flight vehicle at the trim condition of α = -3.85°, δ = 12.16°. These aerodynamic stability derivatives are shown in Table 7.1. Other parameters required by the analytical flight dynamic equations are: mass (*m*) = 607.0464, moment of inertia (*Iy*) = 3346.629, velocity (*U*) = 2423.220, surface area (*S*) = 12.84184, dynamic pressure (*q*) = 36829.69 and reference chord (*c*) = 4.267200.

Table 7.1 Aerodynamic Stability Derivatives of a Scramjet Flight Vehicle

Airframe State	C_D	C_L	C_M
Mean Flow	**1.3070413E-02**	**1.2589106E-02**	**-1.2727222E-06**
Forward Velocity	**1.5813446E-05**	**1.5713536E-05**	**-2.7891413E-06**
Angle of Attack	**-2.0686770E-02**	**0.2707167**	**7.3831538E-03**
Pitch Rate	**7.5796391E-03**	**1.8302677E-03**	**2.0127750E-03**

It can be seen in Table 7.1 that the pitch moment stability derivative of angle of attack (C_{m_α}) is positive; indicating a statically unstable flight vehicle.

Two sets of the ASE module of ASTPE are computed, one without the elastic mode (rigid body modes only) and the other with the first bending mode with natural frequency = 9.755 Hz, and compared to the analytical solution. This comparison is presented in Table 7.2 where an excellent agreement between the ASE module result without the elastic mode and the analytical solution can be seen. Meanwhile, the ASE module result with the first bending mode shows only a slight difference from that with only the rigid modes. This suggests that the structure designed by the SMB module provides sufficient stiffness by which the impact of aeroelastic effects on the flight dynamics is minimized.

Table 7.2 Validation of the ASE module with Analytical Solution.

Longitudinal Dynamics	ASTPE				Analytical (Rigid)	
	+ Bending		Rigid			
	Damping	Frequency	Damping	Frequency	Damping	Frequency
Short Period	-1.0	0.3278 (Hz)	-1.0	0.343 (Hz)	-1.0	0.343 (Hz)
Phugoid	0.772	0.00079 (Hz)	0.729	0.00091(Hz)	0.734	0.00091(Hz)

Note that the negative damping of the short period mode is due to the unstable C_{m_α}, leading to a statically unstable flight vehicle that must be stabilized by a flight control system.

7.4 A Demonstration Case of Flight Control System Design

The state-space equation shown in Equation (7.17) of the plant model is first imported into MATLAB. Subsequently, a Linear Quadratic Guassian Control Method (LQG) compensator shown in Figure 7.7 is designed using the Single Input Single Output (SISO) design tool of the MATLAB Control System Toolbox.

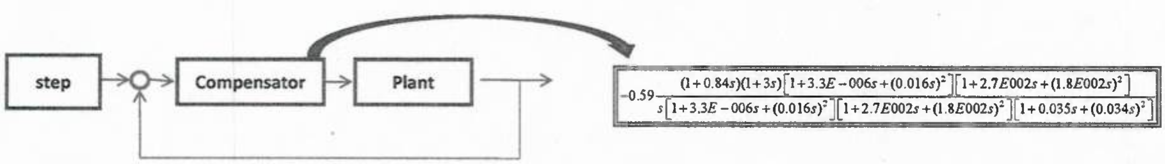
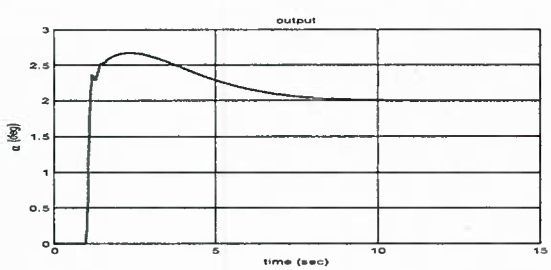


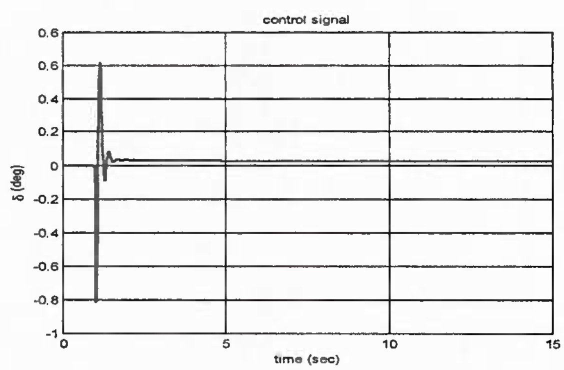
Figure 7.7 A LQG controller

The comparison of the closed-loop result and the open-loop result is presented in Table 7.3. It can be seen that, indeed, the closed-loop is stabilized by the LQG controller. In order to evaluate the performance of the LQG controller, a step input of angle of attack of 2 degrees is introduced and the response the flight vehicle's angle of attack as well as the control surface input shown in Figure 7.8a and 7.8b, respectively. The flight vehicle takes only 7 seconds to reach the desired 2 degrees angle of attack, indicating that the performance of the LQG controller is acceptable.

Table 7.3 Closed-Loop and Open-Loop Results

	Open Loop		Closed Loop	
	damping	frequency	damping	frequency
short period	-1	0.3278 Hz	0.873	0.675 Hz
phugoid	0.772	0.00079 Hz	0.75	0.00565 Hz





(a) Response of Angle-of-Attack (b) Control Surface Input

Figure 7.8 Performance of the LQG controller

Chapter 8 Case Study 1 - Single Engine Missile (SEM)

8.1 Introduction

The Single Engine Missile (SEM) constraints chosen for this study were imposed by maximum allowable dimensions for a missile deployed from either a standard Naval vertical launch system tube (VLS) or an aircraft's missile pylon, as shown in Figure 8.1.1. The work presented in this study could also be applied to other scale vehicles with relatively little effort. The maximum length for this study is constrained to 4.27 m [14 feet] with the maximum width and height being 0.61 m [2 feet] each. These box dimensions result in a maximum available volume V_{max} of 1.59 m^3 [56 ft^3]. An implicit goal in this optimization is to fill this box as much as possible to allow for maximum mass (structural, payload, and fuel) to take advantage of the high lift offered by waverider geometries, while also maximizing the potential for increased missile range (due to the increased fuel volume). However, an increase in volume usually comes at the expense of increased drag (both wave and viscous) which places higher demands on the propulsion system resulting in increased fuel consumption. This is a highly coupled system where only an integrated approach to optimization can lead to a viable result. Due to the nature of the coupling between engine and airframe, the optimal result is not a combination of an optimal engine with an optimal airframe.

One unique additional constraint was imposed on the design: no deployable control surface be integrated into the missile. Since only pitch control was originally investigated, this resulted in a thrust vectored nozzle segment integrated into the scramjet flowpath. For more complex scenarios, this would likely be an undesirable configuration. The baseline configuration is shown in Figure 8.1.2.

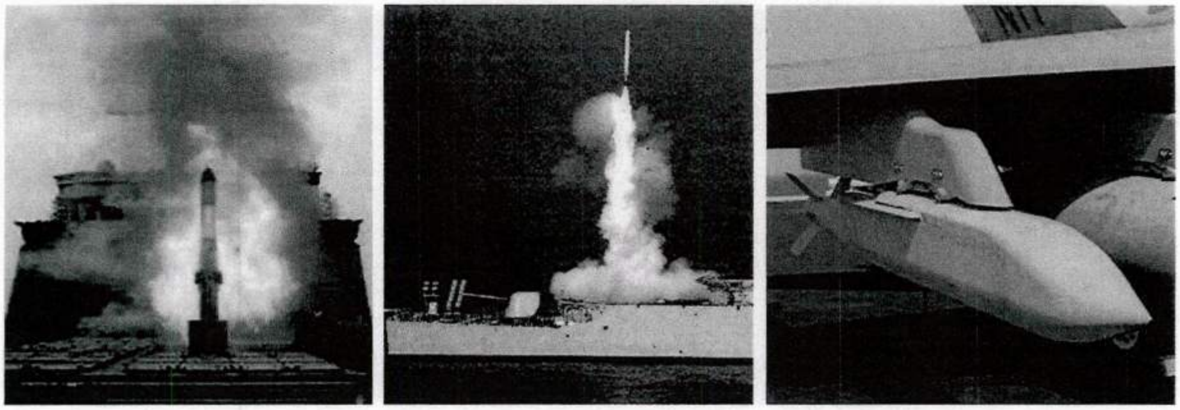


Figure 8.1.1 a) Tomahawk missile exiting a Naval vertical launch tube, b) Tomahawk missile leaving ship, c) Example missile hanging from aircraft pylon (on left side of picture).

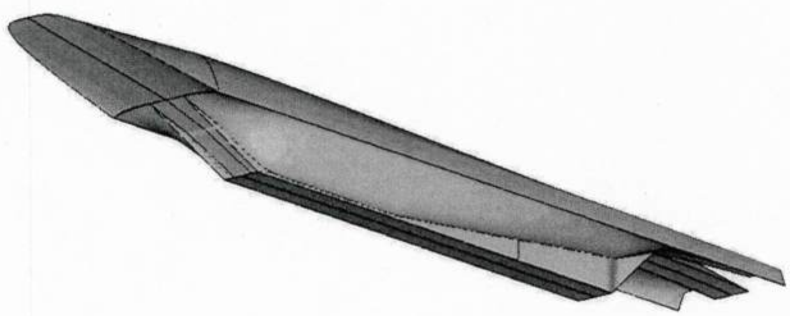


Figure 8.1.2 Baseline SEM model

8.2 Run UCDA to Design the Vehicle

Input Files:

File Name	Type	Remarks	See Listing
vehicle.inp	Standard input file	Also look at Table 8.2.1a and 8.2.1b	Shown in Listing 8.2.1
chem.bin	Engine chemistry information	Required	Shown in Listing 8.2.2

Output Files:

File Name	Type	Remarks	See Listing
plotM060A-010.dat	Standard Tecplot output file	See Fig. 8.2.1	Shown in Listing 8.2.3

Input File descriptions

vehicle.inp: This is a standard input file for UCDA. See listing 8.2.1 for the entire input file. The part that is used to generate the geometry of the vehicle is shown in Tables 8.2.1a and 8.2.1b. Table 8.2.1a shows different patches that are needed to generate the vehicle. There are 16 patches in this SEM vehicle. Each patch should have a name of the patch, the number of grids in the x direction and the number of grids in the y direction. Table 8.2.1b shows the other necessary geometrical and engine input parameters necessary to design the vehicle. The details of the definitions and explanations can be found in the User's Manual.

chem.bin: This is a required input file for the engine chemistry of the vehicle. Chem.bin is generated using ChemKin Version 2 and for this case is a Jet-A reaction mechanism. Please see Listing 8.2.2.

Output File descriptions

plotM060A-010.dat: The output file is a Tecplot format file that can easily be plotted. The plot of the designed vehicle is shown in Figure 8.2.1.

The output file is shown in Listing 8.2.3. The name of this file implies that after designing the vehicle, it was run at Mach 6 (Mxyz in plot file name implying Mach number xy.z) and with an angle of attack -1.0 degrees (A-xyz in plot file name implying angle of attack -xy.z).

The computational run time for UCDA to design a vehicle is about a few seconds.

Table 8.2.1a: Different Zones of SEM Vehicle (see Figure 8.2.2)

ZONE DATA AND GRID SIZES:		
16 NUMBER OF ZONES		
'forebody : top'	31	31
'keel : top'	101	6
'aftbody : top'	101	31
'forebody : bot'	31	31
'ramps : bot'	55	6
'comb : bot'	101	6
'cowl : top'	101	6
'nozzle : bot'	31	6
'ramp walls : inside'	35	6
'comb wall : inside'	101	7
'nozzle wall : inside'	21	7
'aftbody : bot'	101	31
'cowl : bot'	101	6
'ramp walls : outside'	35	6
'comb wall : outside'	101	7
'nozzle wall : outside'	21	7

Table 8.2.1b: Geometrical and Engine Input Parameters of SEM Vehicle

6.0	4	'Mdes' - design Mach number
1.0	0	'AOAdes' - design angle of attack
21800.	1	'Zdes' - design altitude
4.2672	1	'lvehicle' - vehicle length
6.0000	0	'thforclu' - forebody upper surface angle
5.2797	0	'thforcll' - forebody ramp angle
0.5873	1	'lcontrol' - control surface length
7.73	0	'th_control'- control surface deflection angle
0.9920	0	'th_expn' - nozzle initial expansion angle
10.8958	0	'th_exit' - nozzle exit angle
0.0	4	'p_nozpoly' - % diff between nozzle designs [DON'T USE-defaulted to 1.]
1.901	1	'lcowl' - cowl length (isolator/combustor)
.3	1	'lcowlext' - cowl extension length (internal nozzle)
0.545	4	'p_iso' - percent of lcowl that is isolator
.3238	1	'height' - height of vehicle (if required)
20.0	1	'linlet' - inlet length of vehicle (if required)
.26	1	'wengine' - width of the engine (currently defaulted to unit width)
3.00	4	'iramps' - number of inlet ramps in addition to the forebody
6.4012	0	'th_ramp1' - inlet ramp 1 angle
5.2383	0	'th_ramp2' - inlet ramp 2 angle
5.5	0	'th_ramp3' - inlet ramp 3 angle
0.0	0	'th_ramp4' - inlet ramp 4 angle

0.0	0	'th_ramp5' - inlet ramp 5 angle
3.09	0	'th_div1' - first combustor expansion angle
0.2	0	'th_div2' - second combustor expansion angle
0.01	1	'Xinjs' - beginning of injectors (m)
0.02	1	'Xinje' - end of injectors (m)
0.01	1	'Lmix' - fuel mixing length (m)
1.00	4	'eta_mix' - fuel mixing and burning efficiency
3000.	4	'Tlimit' - maximum engine temperature (K)
90.	0	'Thetainj' - injector angle (degrees) [90 deg. is normal to flow]
1200.	4	'Tw' - adiabatic wall temperature (K)
0.1527	4	'nfor' - forebody exponent n
2.0	2	'wfor' - forebody width
1.5	2	'lfor' - forebody length
0.2427	4	'mfor' - forebody exponent m
5.797	0	'thforle' - forebody leading edge angle
21.519	0	'th_le' - leading edge attachment angle
0.0000	4	'p_kl' - keel-line height percentage
0.25	4	'fuelfrac' - vehicle fuel volume fraction
0.0104	2	't_plate' - shell plate thickness (Tungsten)
0.0	4	'mass_smb' - mass due to Structural Modal Base (SMB) analysis
0.0	4	'mass_tps' - mass due to Thermal Protection System (TPS) analysis
0.0	4	'mass_nose' - lumped mass at the nose to manipulate CG

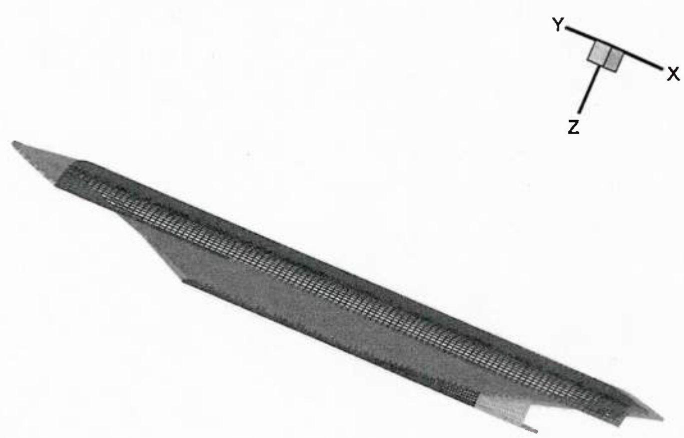
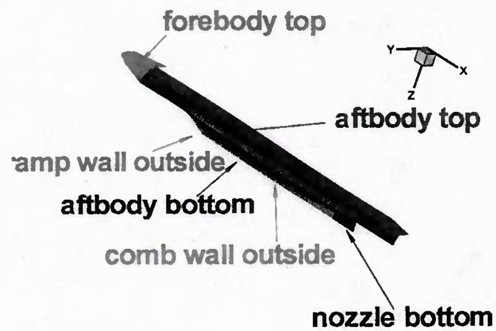
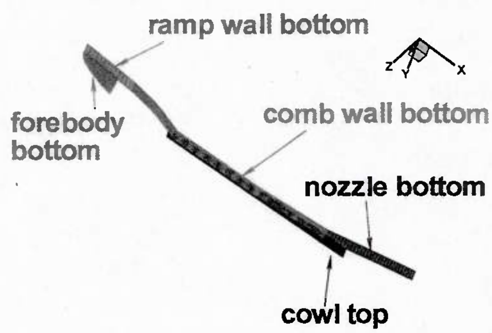


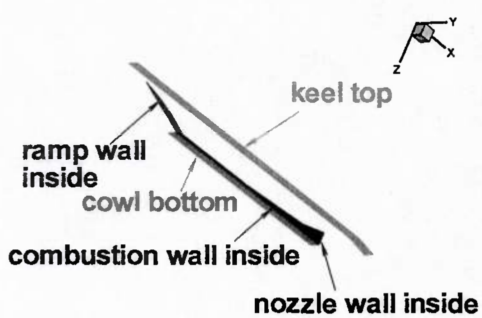
Figure 8.2.1 SEM Vehicle Plot



(a) Selected Zones of SEM Vehicle



(b) Selected Zones of SEM Vehicle



(c) Selected Zones of SEM Vehicle

Figure 8.2.2 Different Zones of SEM Vehicle

Listing 8.2.1: Vehicle.inp Input File

```
TEST INPUT DECK:  Note - this line must be here!
2        ialtdyn - Inlet specified alt. (0), Fixed alt. (1), or Fixed dyn. press. (2)
1        ithrottle - Run engine as a function of: (0) equivalence ratio, (1) % throttle
1        iunits - Output unit switch: SI (1) or English (2)
3        ivisc - Viscous flag: inviscid (1), laminar (2), transitional (3), turbulent (4)
1        iequiv - find max equiv ratio for choked flow: off (0) -> single run, on (1)
2        inozorder - Nozzle polynomial order: 1st (flat plate) -> 3rd
1        iheight - Height constrained vehicle: no (0) = linlet set, yes (1) = height set
2        itrajectory - Run multiple trajectory points: no (0), discrete (1), matrix (2)
0        icone - cone flow data: exact (0), curve-fit approximation (1)
1        imodel - Forebody type: WA (1), VWA (2), or VWA + cone flow (3)
0        itrim - Control surface deflection to trim the vehicle: no (0), yes (1), or optimize (2)
0        ideriv - Calculate derivatives: no (0), yes (1)
0        itps - If itps is 1, then prepare for tps and smb. ideriv and itps cannot be 1 at one time
0        ifeedback - If 1, then gets weight and Cg information from SMB and TPSOPT

OUTPUT FILE SWITCHES AND NAMES:
1   'plot.dat'                      VEHICLEFIG:        off (0), select (1), x,y,z (2), all (3)
3 1 2 3 8 18 23       1st # -> # of variables to read, others -> vars to plot
1   'metrics.dat'                   METRICS:  off (0), on (1)
0   'cowlexit.dat'                  COWLEXIT:          off (0), on (1)
0   'moc.dat'                       NOZFIG:   off (0), P,T,M (1), all (2)
2   'offdesign.dat'                 AOA:      off (0), on (1), UPTOP input tables (2), UPTOP input files (3)
0   'scramjet.dat'                  CKENGINE: off (0), on (1)
0                                   IPRINTINLET:       off (0), all (1), results (2), all-real (3), results-real (4)
0                                   IPRINTENGINE:      off (0), on (1)
0                                   IDEBUG:          off (0), on (1) [print debugging info]

ZONE DATA AND GRID SIZES:
16        NUMBER OF ZONES
'forebody : top'            31       31
'keel : top'              . 101      6
'aftbody : top'             101      31
'forebody : bot'            31       31
'ramps : bot'               55       6
'comb : bot'                101      6
'cowl : top'                101      6
'nozzle : bot'              31       6
'ramp walls : inside'       35       6
'comb wall : inside'        101      7
'nozzle wall : inside'      21       7
'aftbody : bot'             101      31
'cowl : bot'                101      6
'ramp walls : outside'      35       6
'comb wall : outside'       101      7
'nozzle wall : outside'     21       7

INPUT DATA:  (0 = degrees, 1 = m, 2 = ft, 3 = atm, 4 = dimensionless, K or kg, 5 = psf)
xl        x        xu      unit      res name
22500.    26000.   30000.   1        2500.       'altitude' - altitude (if required)
2000.     2200.    2400.0   5        200.        'q0'       - dynamic pressure (if required)
.50       1.099    1.0      4        .250        'equiv'    - equivalence ratio
1.        1.       0.0      4        -.05       'throttle' - engine throttle (if required)
6.0       6.00     8.00     4        .5          'm0'       - Mach number
-2.0      -1.0     3.00     0        .5          'AOA'      - angle of attack
6.0       4        'Mdes'       - design Mach number
1.0       0        'AOAdes'     - design angle of attack
21800.    1        'Zdes'       - design altitude
4.2672    1        'lvehicle'   - vehicle length
6.0000    0        'thforclu'   - forebody upper surface angle
5.2797    0        'thforcll'   - forebody ramp angle
0.5873    1        'lcontrol'   - control surface length
7.73      0        'th_control'- control surface deflection angle
0.9920    0        'th_expn'    - nozzle initial expansion angle
10.8958   0        'th_exit'    - nozzle exit angle
0.0       4        'p_nozpoly'  - % diff between nozzle designs [DON'T USE-defaulted to 1.]
1.901     1        'lcowl'      - cowl length (isolator/combustor)
.3        1        'lcowlext'   - cowl extension length (internal nozzle)
0.545     4        'p_iso'      - percent of lcowl that is isolator
.3238     1        'height'     - height of vehicle (if required)
20.0      1        'linlet'     - inlet length of vehicle (if required)
.26       1        'wengine'    - width of the engine (currently defaulted to unit width)
3.00      4        'iramps'     - number of inlet ramps in addition to the forebody
6.4012    0        'th_ramp1'   - inlet ramp 1 angle
5.2383    0        'th_ramp2'   - inlet ramp 2 angle
5.5       0        'th_ramp3'   - inlet ramp 3 angle
0.0       0        'th_ramp4'   - inlet ramp 4 angle
0.0       0        'th_ramp5'   - inlet ramp 5 angle
3.09      0        'th_div1'    - first combustor expansion angle
0.2       0        'th_div2'    - second combustor expansion angle
0.01      1        'Xinjs'        - beginning of injectors (m)
0.02      1        'Xinje'      - end of injectors (m)
0.01      1        'Lmix'       - fuel mixing length (m)
1.00      4        'eta_mix'    - fuel mixing and burning efficiency
3000.     4        'Tlimit'     - maximum engine temperature (K)
90.       0        'Thetainj'   - injector angle (degrees) [90 deg. is normal to flow]
1200.     4        'Tw'         - adiabatic wall temperature (K)
0.1527    4        'nfor'       - forebody exponent n
2.0       2        'wfor'       - forebody width
```

```
1.5       2      'lfor'      - forebody length
0.2427    4      'mfor'      - forebody exponent m
5.797     0      'thforle'   - forebody leading edge angle
21.519    0      'th_le'     - leading edge attachment angle
0.0000    4      'p_kl'      - keel-line height percentage
0.25      4      'fuelfrac'  - vehicle fuel volume fraction
0.0104    2      't_plate'   - shell plate thickness (Tungsten)
0.0       4      'mass_smb'  - mass due to Structural Modal Base (SMB) analysis
0.0       4      'mass_tps'  - mass due to Thermal Protection System (TPS) analysis
0.0       4      'mass_nose' - lumped mass at the nose to manipulate CG
```

Listing 8.2.2: Chem.bin Input File

```
"3.6             " "DOUBLE          " .F.
 462 624 22 5 17 23 6 10 3 5 3 2 8 3 0 0 0 0 0 0 0 0 10  0.00100000005
 "H              "  1.00796998
 "O              "  15.9994001
 "C              "  12.0111504
 "N              "  14.0066996
 "AR             "  39.9480019
 "O2             " 0 2 0 0 0 0 0  31.9988003 3  300.  1000.  5000.  3.212936
  0.001127486 -5.75615E-07  1.313877E-09 -8.768554E-13 -1005.249  6.034738
  3.697578  0.0006135197 -1.258842E-07  1.775281E-11 -1.136435E-15 -1233.93
  3.189166
 "C12H23         " 23 0 12 0 0 0 0  167.317114 3  273.  1000.  5000.
  2.0869217  0.13314965 -8.1157452E-05  2.9409286E-08 -6.5195213E-12 -35912.814
  27.355289  24.880201  0.078250048 -3.1550973E-05  5.78789E-09 -3.9827968E-13
 -43110.684 -93.655255
 "H2             " 2 0 0 0 0 0 0  2.01593995 3  300.  1000.  5000.  3.298124
  0.0008249442 -8.143015E-07 -9.475434E-11  4.134872E-13 -1012.521 -3.294094
  2.991423  0.0007000644 -5.633829E-08 -9.231578E-12  1.582752E-15 -835.034
 -1.35511
 "H              " 1 0 0 0 0 0 0  1.00796998 3  300.  1000.  5000.  2.5  0.
  0.  0.  0.  25471.63 -0.4601176  2.5  0.  0.  0.  0.  25471.63 -0.4601176
 "O              " 0 1 0 0 0 0 0  15.9994001 3  300.  1000.  5000.  2.946429
 -0.001638166  2.421032E-06 -1.602843E-09  3.890696E-13  29147.64  2.963995
  2.54206 -2.755062E-05 -3.102803E-09  4.551067E-12 -4.368052E-16  29230.8
  4.920308
 "OH             " 1 1 0 0 0 0 0  17.0073701 3  300.  1000.  5000.  3.637266
  0.000185091 -1.676165E-06  2.387203E-09 -8.431442E-13  3606.782  1.35886
  2.88273  0.001013974 -2.276877E-07  2.174684E-11 -5.126305E-16  3886.888
  5.595712
 "HO2            " 1 2 0 0 0 0 0  33.0067703 3  300.  1000.  5000.  2.979963
  0.004996697 -3.790997E-06  2.354192E-09 -8.089024E-13  176.2274  9.222724
  4.072191  0.002131296 -5.308145E-07  6.112269E-11 -2.841165E-15 -157.9727
  3.476029
 "H2O            " 2 1 0 0 0 0 0  18.0153401 3  300.  1000.  5000.  3.386842
  0.003474982 -6.354696E-06  6.968581E-09 -2.506588E-12 -30208.11  2.590233
  2.672146  0.003056293 -8.73026E-07  1.200996E-10 -6.391618E-15 -29899.21
  6.862817
 "CH             " 1 0 1 0 0 0 0  13.0191203 3  300.  1000.  5000.  3.200202
  0.002072876 -5.134431E-06  5.73389E-09 -1.955533E-12  70452.59  3.331588
  2.196223  0.002340381 -7.058201E-07  9.007582E-11 -3.85504E-15  70867.23
  9.178373
 "CO2            " 0 2 1 0 0 0 0  44.0099506 3  300.  1000.  5000.  2.275725
  0.009922072 -1.040911E-05  6.866687E-09 -2.11728E-12 -48373.14  10.18849
  4.453623  0.003140169 -1.278411E-06  2.393997E-10 -1.669033E-14 -48966.96
 -0.9553959
 "CO             " 0 1 1 0 0 0 0  28.0105505 3  300.  1000.  5000.  3.262452
  0.001511941 -3.881755E-06  5.581944E-09 -2.474951E-12 -14310.54  4.848897
  3.025078  0.001442689 -5.630828E-07  1.018581E-10 -6.910952E-15 -14268.35
  6.108218
 "C2H2           " 2 0 2 0 0 0 0  26.0382407 3  300.  1000.  5000.  2.013562
  0.01519045 -1.616319E-05  9.078992E-09 -1.912746E-12  26124.44  8.805378
  4.43677  0.005376039 -1.912817E-06  3.286379E-10 -2.15671E-14  25667.66
 -2.800338
 "N              " 0 0 0 1 0 0 0  14.0066996 3  300.  1000.  5000.  2.503071
 -2.180018E-05  5.420529E-08 -5.64756E-11  2.099904E-14  56098.9  4.167566
  2.450268  0.0001066146 -7.465337E-08  1.879652E-11 -1.025984E-15  56116.04
  4.448758
 "NH             " 1 0 0 1 0 0 0  15.0146695 3  300.  1000.  5000.  3.339758
  0.001253009 -3.491646E-06  4.218812E-09 -1.557618E-12  41850.47  2.507181
  2.760249  0.001375346 -4.451914E-07  7.692792E-11 -5.017592E-15  42078.28
  5.857199
 "NO             " 0 1 0 1 0 0 0  30.0060997 3  300.  1000.  5000.  3.376542
  0.001253063 -3.302751E-06  5.21781E-09 -2.446263E-12  9817.961  5.82959
  3.245435  0.001269138 -5.01589E-07  9.169283E-11 -6.275419E-15  9800.84
  6.417294
 "AR             " 0 0 0 0 1 0 0  39.9480019 3  300.  1000.  5000.  2.5  0.
  0.  0.  0. -745.375  4.366001  2.5  0.  0.  0.  0. -745.375  4.366001
 "N2             " 0 0 0 2 0 0 0  28.0133991 3  300.  1000.  5000.  3.298677
  0.00140824 -3.963222E-06  5.641515E-09 -2.444855E-12 -1020.9  3.950372
  2.92664  0.001487977 -5.684761E-07  1.009704E-10 -6.753351E-15 -922.7977
  5.980528
 -5 2  4.35E+09  0.  15098.1385 -1 2 -1 17 0 0 12 9 11 4 1 17 5 3  1.E+15  0.
  39255.16 -1 3 -1 17 -1 9 1 9 2 14 0 0 6 3  1.6E+09  0.5  22093.6093 -1 5 -1 17
 -1 7 2 15 1 4 1 5 4 2  3.E+13  1.  19124.3087 -1 3 -1 1 0 0 1 8 1 5 0 0 4 2
  2.5E+15  0.  3019.62769 -1 3 -1 5 0 0 1 4 1 6 0 0 4 2  4.E+14  0.  9058.88307
 -1 4 -1 1 0 0 1 5 1 6 0 0 4 2  1.E+18  0.  61519.3782 -1 17 -1 1 0 0 2 5 1 17 0
```

```
0 3 2  4.E+20 -1.  0. -1 3 -2 4 0 0 2 3 0 0 0 0 3 2  1.E+15 -1.15  0. -1 4 -1 1
0 0 1 7 0 0 0 0 4 2  1.E+13  0.  0. -1 6 -1 7 0 0 1 8 1 1 0 0 4 2  6.5E+13  0.
 0. -1 4 -1 7 0 0 1 3 1 1 0 0 4 2  2.5E+13  0.  0. -1 5 -1 7 0 0 1 6 1 1 0 0 4
2  15100000.  1.28 -381.479632 -1 11 -1 6 0 0 1 10 1 4 0 0 4 2  1.5E+17  0.
-381.479632 -1 17 -2 9 0 0 1 12 1 17 0 0 4 2  3.E+15  0.  9562.15435 -1 12 -1 1
0 0 2 11 1 3 0 0 4 2  3.E+13  0.  3019.62769 -1 9 -1 6 0 0 1 11 1 3 0 0 4 2
 3.E+12  0.6  0. -1 9 -1 5 0 0 1 11 1 4 0 0 4 2  1.E+11  0.  0. -1 9 -1 15 0 0
1 14 1 11 0 0 4 2  9.E+13  0.  37745.3461 -1 17 -1 5 0 0 1 13 1 15 0 0 4 2
 6.3E+09  1.  3170.60907 -1 13 -1 1 0 0 1 15 1 5 0 0 4 2  1.E+12  0.
 24157.0215 -1 15 -1 4 0 0 1 13 1 6 0 0 4 2  25000.  2.64  0. -1 14 -1 5 0 0 1
15 1 4 0 0 4 2  2.E+15 -0.8  0. -1 14 -1 15 0 0 1 17 1 6 0 0
2  1.95E+15  0.  0. 3  2.5E+10  0.  4026.17025 7  4.E+18  0.  0.
```

Listing 8.2.3: PLOTM060A-010.DAT TECPLOT output file

```
variables =
 "x"
 "y"
 "z"
 zone f=block, t="forebody : top           ",                    i=         31
 ,j=          31
  0.0000000000E+00
  0.9738366363E-10
  0.9117331778E-08
  0.1297335075E-06
  0.8535901657E-06
  0.3680378768E-05
  0.1214601616E-04
  0.3333144195E-04
  0.7991550956E-04
  0.1728295756E-03
  0.3445673501E-03
  0.6432000082E-03
  0.1137144165E-02
  0.1920724637E-02
  0.3120583249E-02
  0.4902962130E-02
  0.7481913548E-02
  0.1112846565E-01
  0.1618078910E-01
  0.2305538580E-01
  0.3225936368E-01
  0.4440378770E-01
  0.6021819264E-01
  0.8056626469E-01
  0.1064626127E+00
  0.1390910000E+00
  0.1798236370E+00
  .........
  .........
  .........
  .........
  .........

  0.2112343460E+00
  0.2393971682E+00
  0.2393971682E+00
  0.9475558996E-01
  0.1236315519E+00
  0.1525074989E+00
  0.1813834608E+00
  0.2102594078E+00
  0.2391353548E+00
  0.2391353548E+00
```

8.3 Run UCDA to Generate Tables and Input Files for UPTOP

This section corresponds to the Step 1 in the Graphical User Interface (GUI). See Figure 8.3.1 below.

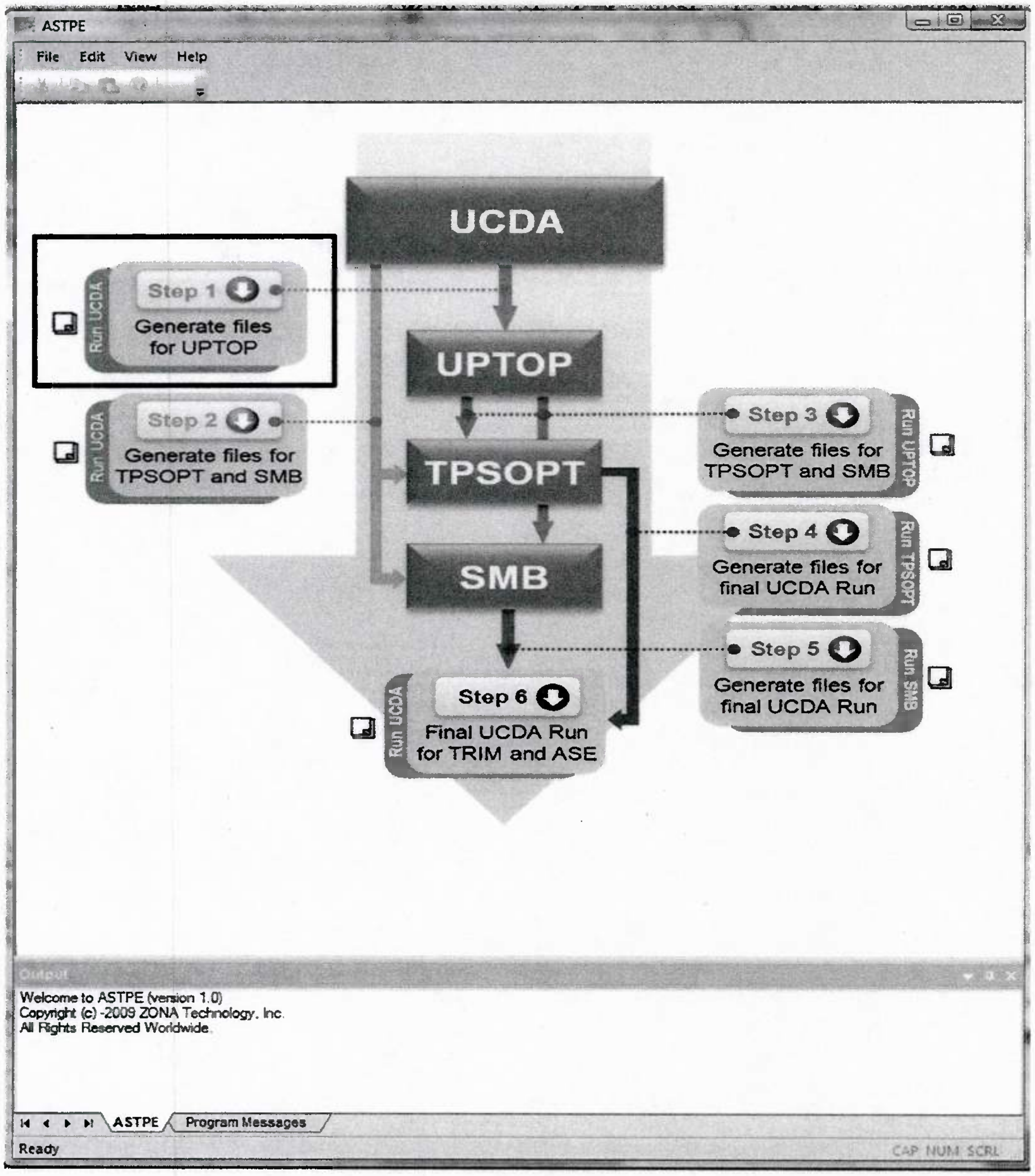


Figure 8.3.1 Section Corresponding to Step 1 of GUI

8.3.1 Generate Tab Files

Input Files:

File Name	Type	Remarks	See Listing
vehicle.inp	Standard input file	Also look at Table 8.3.1.a 8.3.1b	Shown in Listing 8.3.1
chem.bin	Engine chemistry information	Required	Shown in Listing 8.2.2

Output Files:

File Name	Type	Remarks	See Listing
lift.tab	Tabular format	Aerodynamic information for UPTOP	Shown in Listing 8.3.2
drag.tab	Tabular format	Aerodynamic information for UPTOP	Shown in Listing 8.3.3
fuel.tab	Tabular format	Aerodynamic information for UPTOP	Shown in Listing 8.3.4
thr.tab	Tabular format	Aerodynamic information for UPTOP	Shown in Listing 8.3.5

Input File descriptions

vehicle.inp: See Listing 8.3.1 for the entire input file. The parts of the input file that are used to generate the tables for UPTOP are displayed in Tables 8.3.1a and 8.3.1b. Table 8.3.1a shows the necessary parameters to control the creation of such tables and Table 8.3.1b shows a matrix of trajectory points. It can be noted that to generate tables for UPTOP, **itrajectory** has to be set to **2** and **offdesign.dat** switch has to be set to **2**. These are the only change needed from the earlier run of Section 8.2.

Different points on the trajectory are defined by the way shown in Table 8.3.1b. There are six lines in Table 8.3.1b. Each line has its own parameter such as altitude, dynamic pressure, throttle etc. Since **ialtdyn** is set to **2** (Table 8.3.1a), the code does not need to run corresponding to the altitude. Also, since **ithrottle** is set to **1**, the line with the Equivalence ratio is not used. More discussions on this can be found in the User's Manual. Thus, the code goes through the rest of the four variables. Each variable has got its lower bound and upper bound defined in the

first and third number from the left. Also, the fifth variable is the value of its interval. For example, for Mach number, the lower bound is 6.0, upper bound is 8.0 and interval is 0.5. Thus, the code will run through 5 points for Mach number. Similarly, each of these four parameters has such bounds and intervals. Thus, the code runs a combination of all possible points, which is a total of 3 dynamic pressure points x 21 throttle points x 5 mach number points x 11 angle of attack points = 3465 points.

<u>chem.bin</u>: This file remains the same for all UCDA runs. Please see Section 8.2 for description on this file.

Table 8.3.1a Necessary Blocks Controlling TAB File Creation for UPTOP

```
TEST INPUT DECK:  Note - this line must be here!
2          ialtdyn - Inlet specified alt. (0), Fixed alt. (1), or Fixed dyn. press. (2)
1          ithrottle - Run engine as a function of: (0) equivalence ratio, (1) % throttle
1          iunits - Output unit switch: SI (1) or English (2)
3          ivisc - Viscous flag: inviscid (1), laminar (2), transitional (3), turbulent (4)
1          iequiv - find max equiv ratio for choked flow: off (0) -> single run, on (1)
2          inozorder - Nozzle polynomial order: 1st (flat plate) -> 3rd
1          iheight - Height constrained vehicle: no (0) = linlet set, yes (1) = height set
2          itrajectory - Run multiple trajectory points: no (0), discrete (1), matrix (2)
0          icone - cone flow data: exact (0), curve-fit approximation (1)
1          imodel - Forebody type: WA (1), VWA (2), or VWA + cone flow (3)
0          itrim - Control surface deflection to trim the vehicle: no (0), yes (1), or optimize (2)
0          ideriv - Calculate derivatives: no (0), yes (1)
0          tps - If itps is 1, then prepare for tps and smb. ideriv and itps cannot be 1 at one time
0          ifeedback - If 1, then gets weight and Cg information from SMB and TPSOPT

OUTPUT FILE SWITCHES AND NAMES:
1  'plot.dat'            VEHICLEFIG:     off (0), select (1), x,y,z (2), all (3)
3 1 2 3 8 18 23      1st # -> # of variables to read, others -> vars to plot
1  'metrics.dat'         METRICS:        off (0), on (1)
0  'cowlexit.dat'        COWLEXIT:       off (0), on (1)
0  'moc.dat'             NOZFIG: off (0), P,T,M (1), all (2)
2  'offdesign.dat'       AOA:      off (0), on (1), UPTOP input tables (2), UPTOP input files (3)
0  'scramjet.dat'        CKENGINE:       off (0), on (1)
0                        IPRINTINLET:    off (0), all (1), results (2), all-real (3), results-real (4)
0                        IPRINTENGINE:   off (0), on (1)
0                        IDEBUG:      off (0), on (1) [print debugging info]
```

Table 8.3.1b Necessary Blocks to Run a Matrix of Points to Generate Table

```
INPUT DATA:  (0 = degrees, 1 = m, 2 = ft, 3 = atm, 4 = dimensionless, K or kg, 5 = psf)
xl        x         xu        unit      res       name
22500.    26000.    30000.    1         2500.     'altitude' - altitude (if required)
```

2000.	2200.	2400.0	5	200.	'q0'	- dynamic pressure (if required)
.50	1.099	1.0	4	.250	'equiv'	- equivalence ratio
1.	1.	0.0	4	-.05	'throttle'	- engine throttle (if required)
6.0	6.00	8.00	4	.5	'm0'	- Mach number
-2.0	-1.0	3.00	0	.5	'AOA'	- angle of attack

Output File Descriptions

lift.tab: For each of the points described above, lift is tabulated in this file. Please see Listing 8.3.2.

drag.tab: For each of the points described above, drag is tabulated in this file. Please see Listing 8.3.3.

fuel.tab: For each of the points described above, fuel is tabulated in this file. Please see Listing 8.3.4.

thr.tab: For each of the points described above, thrust is tabulated in this file. Please see Listing 8.3.5.

UPTOP requires these four tabulated results to find the optimized trajectory.

The computational run time to generate the *.tab files for UPTOP is approximately 1 hour for sample SEM.

8.3.2 Generate Input Files

Input Files:

File Name	Type	Remarks	See Listing
vehicle.inp	Standard input file	Also look at Table 8.3.2	Shown in Listing 8.3.6
chem.bin	Engine chemistry information	Required and does not change	Shown in Listing 8.2.2

Output Files:

File Name	Type	Remarks	See Listing
traj.inp	Standard input for UPTOP	Main input file for UPTOP	Shown in Listing 8.3.7
model.inp	Standard input for UPTOP	Information about model	Shown in Listing 8.3.8

Input File Descriptions

vehicle.inp: See Listing 8.3.6 for the entire input file. The part of the input file that is used to generate the input files model.inp and traj.inp for UPTOP is shown in Tables 8.3.2. It can be seen comparing Listings 8.3.1 and 8.3.6 that the only changes between these two vehicle.inps are in the parameters **itrajectory** and **offdesign.dat** file switch. For the generation of the *.tab files, **itrajectory** was set to **2**. Here, as noted in Table 8.3.2, **itrajectory** is set to **0**. The flag for **offdesign.dat** is changed to **3** from **2**. These changes will generate model.inp and traj.inp.

Table 8.3.2: Changes in Input from Table 8.3.1a for Generating INP Files

TEST INPUT DECK: Note - this line must be here!			
2	ialtdyn - Inlet specified alt. (0), Fixed alt. (1), or Fixed dyn. press. (2)		
1	ithrottle - Run engine as a function of: (0) equivalence ratio, (1) % throttle		
1	iunits - Output unit switch: SI (1) or English (2)		
3	ivisc - Viscous flag: inviscid (1), laminar (2), transitional (3), turbulent (4)		
1	iequiv - find max equiv ratio for choked flow: off (0) -> single run, on (1)		
2	inozorder - Nozzle polynomial order: 1st (flat plate) -> 3rd		
1	iheight - Height constrained vehicle: no (0) = linlet set, yes (1) = height set		
0	itrajectory - Run multiple trajectory points: no (0), discrete (1), matrix (2)		
0	icone - cone flow data: exact (0), curve-fit approximation (1)		
1	imodel - Forebody type: WA (1), VWA (2), or VWA + cone flow (3)		
0	itrim - Control surface deflection to trim the vehicle: no (0), yes (1), or optimize (2)		
0	ideriv - Calculate derivatives: no (0), yes (1)		
0	itps - If itps is 1, then prepare for tps and smb. ideriv and itps cannot be 1 at one time		
0	ifeedback - If 1, then gets weight and Cg information from SMB and TPSOPT		
OUTPUT FILE SWITCHES AND NAMES:			
1	'plot.dat'	VEHICLEFIG:	off (0), select (1), x,y,z (2), all (3)
3 1 2 3 8 18 23	1st # -> # of variables to read, others -> vars to plot		
1	'metrics.dat'	METRICS:	off (0), on (1)
0	'cowlexit.dat'	COWLEXIT:	off (0), on (1)
0	'moc.dat'	NOZFIG:	off (0), P,T,M (1), all (2)
3	'offdesign.dat'	AOA:	off (0), on (1), UPTOP input tables (2), UPTOP input files (3)
0	'scramjet.dat'	CKENGINE:	off (0), on (1)
0		IPRINTINLET:	off (0), all (1), results (2), all-real (3), results-real (4)
0		IPRINTENGINE:	off (0), on (1)
0		IDEBUG:	off (0), on (1) [print debugging info]

Output File descriptions

traj.inp: See Listing 8.3.7 for this output. This file is the main input file for UPTOP. It contains information about orientation parameters, optimization parameters, event parameters, engine throttle control etc. Please see Section 4.5.1 of User's Manual for detailed description.

model.inp: See Listing 8.3.8 for this output that is used by UPTOP as a standard input file. This file contains information about number of components, engine, fuel tank etc. The detailed explanation of this file can be found in Section 4.5.4 of User's Manual.

The computational run time to generate the input files for UPTOP is about a few seconds.

Listing 8.3.1: Vehicle.inp Input File for UPTOP Tab File Generation

```
TEST INPUT OECK:  Note - this line must be here!
2         ialtdyn - Inlet specified alt. (0), Fixed alt. (1), or Fixed dyn. press. (2)
1         ithrottle - Run engine as a function of: (0) equivalence ratio, (1) % throttle
1         iunits - Output unit switch: SI (1) or English (2)
3         ivisc - Viscous flag: inviscid (1), laminar (2), transitional (3), turbulent (4)
1         iequiv - find max equiv ratio for choked flow: off (0) -> single run, on (1)
2         inozorder - Nozzle polynomial order: 1st (flat plate) -> 3rd
1         iheight - Height constrained vehicle: no (0) = linlet set, yes (1) = height set
2         itrajectory - Run multiple trajectory points: no (0), discrete (1), matrix (2)
0         icone - cone flow data: exact (0), curve-fit approximation (1)
1         imodel - Forebody type: WA (1), VWA (2), or VWA + cone flow (3)
0         itrim - Control surface deflection to trim the vehicle: no (0), yes (1), or optimize (2)
0         ideriv - Calculate derivatives: no (0), yes (1)
0         itps - If itps is 1, then prepare for tps and smb. ideriv and itps cannot be 1 at one time
0         ifeedback - If 1, then gets weight and Cg information from SMB and TPSOPT

OUTPUT FILE SWITCHES AND NAMES:
1   'plot.dat'                       VEHICLEFIG:         off (0), select (1), x,y,z (2), all (3)
3 1 2 3 8 18 23         1st # -> # of variables to read, others -> vars to plot
1   'metrics.dat'                    METRICS:  off (0), on (1)
0   'cowlexit.dat'                   COWLEXIT:           off (0), on (1)
0   'moc.dat'                        NOZFIG:   off (0), P,T,M (1), all (2)
2   'offdesign.dat'                  AOA:           off (0), on (1), UPTOP input tables (2), UPTOP input files (3)
0   'scramjet.dat'                   CKENGINE: off (0), on (1)
0                                    IPRINTINLET:        off (0), all (1), results (2), all-real (3), results-real (4)
0                                    IPRINTENGINE:       off (0), on (1)
0                                    IDEBUG:           off (0), on (1) [print debugging info]

ZONE DATA AND GRID SIZES:
16        NUMBER OF ZONES
'forebody : top'            31          31
'keel : top'                101         6
'aftbody : top'             101         31
'forebody : bot'            31          31
'ramps : bot'               55          6
'comb : bot'                101         6
'cowl : top'                101         6
'nozzle : bot'              31          6
'ramp walls : inside'       35          6
'comb wall : inside'        101         7
'nozzle wall : inside'      21          7
'aftbody : bot'             101         31
'cowl : bot'                101         6
'ramp walls : outside'      35          6
'comb wall : outside'       101         7
'nozzle wall : outside'     21          7

INPUT OATA:  (0 = degrees, 1 = m, 2 = ft, 3 = atm, 4 = dimensionless, K or kg, 5 = psf)
xl        x         xu      unit       res name
22500.    26000.    30000.    1        2500.        'altitude' - altitude (if required)
2000.     2200.     2400.0    5        200.         'q0'       - dynamic pressure (if required)
.50       1.099     1.0       4       .250          'equiv'    - equivalence ratio
1.        1.        0.0       4       -.05         'throttle' - engine throttle (if required)
6.0       6.00      8.00      4        .5           'm0'       - Mach number
-2.0      -1.0      3.00      0        .5           'AOA'      - angle of attack
6.0       4         'Mdes'       - design Mach number
1.0       0         'AOAdes'     - design angle of attack
21800.    1         'Zdes'       - design altitude
4.2672    1         'lvehicle'   - vehicle length
6.0000    0         'thforclu'   - forebody upper surface angle
5.2797    0         'thforcll'   - forebody ramp angle
0.5873    1         'lcontrol'   - control surface length
7.73      0         'th_control'- control surface deflection angle
0.9920    0         'th_expn'    - nozzle initial expansion angle
10.8958   0         'th_exit'    - nozzle exit angle
0.0       4         'p_nozpoly' - % diff between nozzle designs [DON'T USE-defaulted to 1.]
1.901     1         'lcowl'      - cowl length (isolator/combustor)
```

```
.3        1        'lcowlext'  - cowl extension length (internal nozzle)
0.545     4        'p_iso'     - percent of lcowl that is isolator
.3238     1        'height'    - height of vehicle (if required)
20.0      1        'linlet'    - inlet length of vehicle (if required)
.26       1        'wengine'   - width of the engine (currently defaulted to unit width)
3.00      4        'iramps'    - number of inlet ramps in addition to the forebody
6.4012    0        'th_ramp1'  - inlet ramp 1 angle
5.2383    0        'th_ramp2'  - inlet ramp 2 angle
5.5       0        'th_ramp3'  - inlet ramp 3 angle
0.0       0        'th_ramp4'  - inlet ramp 4 angle
0.0       0        'th_ramp5'  - inlet ramp 5 angle
3.09      0        'th_div1'   - first combustor expansion angle
0.2       0        'th_div2'   - second combustor expansion angle
0.01      1        'Xinjs'       - beginning of injectors (m)
0.02      1        'Xinje'     - end of injectors (m)
0.01      1        'Lmix'      - fuel mixing length (m)
1.00      4        'eta_mix'   - fuel mixing and burning efficiency
3000.     4        'Tlimit'    - maximum engine temperature (K)
90.       0        'Thetainj'  - injector angle (degrees) [90 deg. is normal to flow]
1200.     4        'Tw'        - adiabatic wall temperature (K)
0.1527    4        'nfor'      - forebody exponent n
2.0       2        'wfor'      - forebody width
1.5       2        'lfor'      - forebody length
0.2427    4        'mfor'      - forebody exponent m
5.797     0        'thforle'   - forebody leading edge angle
21.519    0        'th_le'     - leading edge attachment angle
0.0000    4        'p_kl'      - keel-line height percentage
0.25      4        'fuelfrac'  - vehicle fuel volume fraction
0.0104    2        't_plate'   - shell plate thickness (Tungsten)
0.0       4        'mass_smb'  - mass due to Structural Modal Base (SMB) analysis
0.0       4        'mass_tps'  - mass due to Thermal Protection System (TPS) analysis
0.0       4        'mass_nose' - lumped mass at the nose to manipulate CG
```

Listing 8.3.2: Lift.tab Output File From UCDA / Input File for UPTOP

```
1
           4
           3          10
           5          11
          11          30
          21         201
 1 0
   95760.52
   105336.6
   114912.6
   6.000000
   6.500000
   7.000000
   7.500000
   8.000000
  -2.000000
  -1.500000
  -1.000000
 -0.5000000
  0.0000000E+00
  0.5000000
   1.000000
   1.500000
   2.000000
   2.500000
   3.000000
   1.000000
  0.9500000
  0.9000000
  0.8500000
  0.8000000
  0.7500000
  0.7000000
  0.6500000
  0.6000000
  0.5500000
  0.5000000
  0.4500000
  0.4000000
  0.3500000
  0.3000000
  0.2500000
  0.2000000
  0.1500000
----
----
----
----
  6.1231308E-02
  6.0872644E-02
  6.0495283E-02
```

```
5.9861157E-02
5.9576988E-02
7.5901493E-02
7.5594895E-02
7.5364500E-02
7.5144343E-02
7.4288003E-02
7.3953614E-02
7.3910423E-02
7.3712774E-02
7.3261432E-02
7.2765857E-02
7.2147928E-02
7.2014943E-02
7.1837217E-02
7.1294241E-02
7.0829764E-02
7.0054948E-02
6.9974072E-02
6.9765061E-02
6.9011092E-02
6.8698600E-02
6.8210095E-02
```

Listing 8.3.3: Drag.tab Output File From UCDA / Input File for UPTOP

```
1
          4
          3           10
          5           11
         11           30
         21          201
 1 0
   95760.52
   105336.6
   114912.6
   6.000000
   6.500000
   7.000000
   7.500000
   8.000000
  -2.000000
  -1.500000
  -1.000000
 -0.5000000
  0.0000000E+00
  0.5000000
   1.000000
   1.500000
   2.000000
   2.500000
   3.000000
   1.000000
  0.9500000
  0.9000000
  0.8500000
  0.8000000
  0.7500000
  0.7000000
  0.6500000
  0.6000000
  0.5500000
  0.5000000
  0.4500000
  0.4000000
  0.3500000
  0.3000000
  0.2500000
  0.2000000

----
----
----
----
  8.3374046E-03
  9.0313768E-03
  9.6361507E-03
  1.0392137E-02
  1.1000030E-02
  1.1595636E-02
  1.2130089E-02
  1.2826661E-02
  1.3497436E-02
  1.4106624E-02
  1.4658505E-02
  1.5280219E-02
  1.5944134E-02
```

```
1.6530558E-02
1.7155927E-02
1.7733576E-02
1.8403927E-02
1.9007692E-02
1.9560510E-02
2.0167571E-02
2.0705635E-02
1.1527042E-02
1.2119142E-02
1.2714200E-02
1.3287483E-02
1.3990060E-02
1.4618386E-02
1.5112401E-02
1.5638512E-02
1.6221626E-02
1.6789125E-02
1.7442724E-02
1.7956434E-02
1.8487418E-02
1.9095829E-02
1.9659458E-02
2.0250056E-02
2.0792818E-02
2.1308286E-02
2.1880256E-02
2.2395287E-02
2.2949908E-02
```

Listing 8.3.4: Fuel.tab Output File From UCDA / Input File for UPTOP

```
1
           4
           3          10
           5          11
          11          30
          21         201
 1 0
   95760.52
   105336.6
   114912.6
   6.000000
   6.500000
   7.000000
   7.500000
   8.000000
  -2.000000
  -1.500000
  -1.000000
 -0.5000000
  0.0000000E+00
  0.5000000
   1.000000
   1.500000
   2.000000
   2.500000
   3.000000
   1.000000
  0.9500000
  0.9000000
  0.8500000
  0.8000000
  0.7500000
  0.7000000
  0.6500000
  0.6000000
  0.5500000
  0.5000000
  0.4500000
  0.4000000
  0.3500000
  0.3000000
  0.2500000
----
----
----
  0.2366534
  0.2208765
  0.2050996
  0.1893227
  0.1735458
  0.1577689
  0.1419920
  0.1262151
  0.1104382
  9.4661348E-02
  7.8884453E-02
  6.3107565E-02
```

```
  4.7330674E-02
  3.1553783E-02
  1.5776888E-02
 -4.7018802E-09
  0.2897106
  0.2752251
  0.2607396
  0.2462541
  0.2317685
  0.2172830
  0.2027974
  0.1883119
  0.1738264
  0.1593409
  0.1448553
  0.1303698
  0.1158843
  0.1013987
  8.6913191E-02
  7.2427660E-02
  5.7942126E-02
  4.3456595E-02
  2.8971061E-02
  1.4485528E-02
 -4.3170250E-09
```

Listing 8.3.5: Thr.tab Output File From UCDA / Input File for UPTOP

```
1
           4
           3          10
           5          11
          11          30
          21         201
 1 0
   95760.52
   105336.6
   114912.6
   6.000000
   6.500000
   7.000000
   7.500000
   8.000000
  -2.000000
  -1.500000
  -1.000000
 -0.5000000
  0.0000000E+00
  0.5000000
   1.000000
   1.500000
   2.000000
   2.500000
   3.000000
   1.000000
  0.9500000
  0.9000000
  0.8500000
  0.8000000
  0.7500000
  0.7000000
  0.6500000
  0.6000000
  0.5500000
  0.5000000
  0.4500000
  0.4000000
  0.3500000
  0.3000000
  0.2500000
  0.2000000
  0.1500000
  9.9999987E-02
  4.9999986E-02
 -1.4901161E-08
  5.6110002E-02
----
----
----
  0.1552322
  0.1324296
  0.1117751
  9.2845812E-02
  7.2162598E-02
  5.3708833E-02
  0.4407576
```

```
0.0       4        'p_nozpoly' - % diff between nozzle designs [DON'T USE-defaulted to 1.]
1.901     1        'lcowl'     - cowl length (isolator/combustor)
.3        1        'lcowlext'  - cowl extension length (internal nozzle)
0.545     4        'p_iso'     - percent of lcowl that is isolator
.3238     1        'height'    - height of vehicle (if required)
20.0      1        'linlet'    - inlet length of vehicle (if required)
:26       1        'wengine'   - width of the engine (currently defaulted to unit width)
3.00      4        'iramps'    - number of inlet ramps in addition to the forebody
6.4012    0        'th_ramp1'  - inlet ramp 1 angle
5.2383    0        'th_ramp2'  - inlet ramp 2 angle
5.5       0        'th_ramp3'  - inlet ramp 3 angle
0.0       0        'th_ramp4'  - inlet ramp 4 angle
0.0       0        'th_ramp5'  - inlet ramp 5 angle
3.09      0        'th_div1'   - first combustor expansion angle
0.2       0        'th_div2'   - second combustor expansion angle
0.01      1        'Xinjs'       - beginning of injectors (m)
0.02      1        'Xinje'     - end of injectors (m)
0.01      1        'Lmix'      - fuel mixing length (m)
1.00      4        'eta_mix'   - fuel mixing and burning efficiency
3000.     4        'Tlimit'    - maximum engine temperature (K)
90.       0        'Thetainj'  - injector angle (degrees) [90 deg. is normal to flow]
1200.     4        'Tw'        - adiabatic wall temperature (K)
0.1527    4        'nfor'      - forebody exponent n
2.0       2        'wfor'      - forebody width
1.5       2        'lfor'      - forebody length
0.2427    4        'mfor'      - forebody exponent m
5.797     0        'thforle'   - forebody leading edge angle
21.519    0        'th_le'     - leading edge attachment angle
0.0000    4        'p_kl'      - keel-line height percentage
0.25      4        'fuelfrac'  - vehicle fuel volume fraction
0.0104    2        't_plate'   - shell plate thickness (Tungsten)
0.0       4        'mass_smb'  - mass due to Structural Modal Base (SMB) analysis
0.0       4        'mass_tps'  - mass due to Thermal Protection System (TPS) analysis
0.0       4        'mass_nose' - lumped mass at the nose to manipulate CG
```

Listing 8.3.7: Traj.inp Output File From UCDA / Input File for UPTOP

```
RUN METHOD
 10  (0-single case, 1-new GA, 2-restart, 3-mapspace)

OPTIMIZATION VARIABLES
INITIAL CONDITIONS
ON/OFF       Xo        XL        XU       VARIABLE NAME
-----------------------------------------------------------------------------
 1  23693.8  21233.2  26154.4  initial altitude (m)
 0      0.0    -10.0     10.0  initial gamma
 1     -6.2     -8.0     -6.0  initial velocity (m/s)

ORIENTATION PARAMETERS
2  Mode (1 - rpy, 2 - aeroballistic angles)
-----------------------------------------------------------------------------
 30  angle 1 id
 0  Variable Mode
 1  Curve fit order
 1  Independent Variable type
 2  Number of Control Points
  0  0    0.0    1.0   10.0
  0  0  500.0    1.0   10.0
  1  0   -1.5   -2.0    3.0
  1  0   -1.0   -2.0    3.0

 32  angle 1 id
 2  Variable Mode
 0  0  0  0

 31  angle 1 id
 2  Variable Mode
 0  0  0  0

EVENT PARAMETERS
 0  Number of Control Points
 Type  info(2)  info(3) Type     Var     Xo      Xl     Xu
-----------------------------------------------------------------------------

ENGINE THROTTLE CONTROLS
 1  Number of engine specifications
 -----------
 1  Engine Number
 2  Specification Type
 0  1  0  0

TERMINATION PARAMETERS
 Opt      Info(1)  Var      Value   Xl      Xu
-----------------------------------------------------------------------------
 0  0  -551  1.  0  0

NAVIGATION PARAMETERS
-----------------------------------------------------------------------------
 0  0.  0.  10.   mu
```

```
0.4207702
0.4006385
0.3812354
0.3575782
0.3362620
0.3194262
0.3015297
0.2817416
0.2624639
0.2402709
0.2227190
0.2045566
0.1838708
0.1646255
0.1444584
0.1258453
0.1081174
8.8576645E-02
7.0929833E-02
5.1928550E-02
```

Listing 8.3.6: Vehicle.inp Input File for UPTOP Input (INP) File Generation

```
TEST INPUT DECK:  Note - this line must be here!
2         ialtdyn - Inlet specified alt. (0), Fixed alt. (1), or Fixed dyn. press. (2)
1         ithrottle - Run engine as a function of: (0) equivalence ratio, (1) % throttle
1         iunits - Output unit switch: SI (1) or English (2)
3         ivisc - Viscous flag: inviscid (1), laminar (2), transitional (3), turbulent (4)
1         iequiv - find max equiv ratio for choked flow: off (0) -> single run, on (1)
2         inozorder - Nozzle polynomial order: 1st (flat plate) -> 3rd
1         iheight - Height constrained vehicle: no (0) = linlet set, yes (1) = height set
0         itrajectory - Run multiple trajectory points: no (0), discrete (1), matrix (2)
0         icone - cone flow data: exact (0), curve-fit approximation (1)
1         imodel - Forebody type: WA (1), VWA (2), or VWA + cone flow (3)
0         itrim - Control surface deflection to trim the vehicle: no (0), yes (1), or optimize (2)
0         ideriv - Calculate derivatives: no (0), yes (1)
0         itps - If itps is 1, then prepare for tps and smb. ideriv and itps cannot be 1 at one time
0         ifeedback - If 1, then gets weight and Cg information from SMB and TPSOPT

OUTPUT FILE SWITCHES AND NAMES:
1   'plot.dat'                        VEHICLEFIG:        off (0), select (1), x,y,z (2), all (3)
3 1 2 3 8 18 23       1st # -> # of variables to read, others -> vars to plot
1   'metrics.dat'                     METRICS:  off (0), on (1)
0   'cowlexit.dat'                    COWLEXIT:          off (0), on (1)
0   'moc.dat'                         NOZFIG:   off (0), P,T,M (1), all (2)
3   'offdesign.dat'                   AOA:      off (0), on (1), UPTOP input tables (2), UPTOP input files (3)
0   'scramjet.dat'                    CKENGINE: off (0), on (1)
0                                     IPRINTINLET:       off (0), all (1), results (2), all-real (3), results-real (4)
0                                     IPRINTENGINE:      off (0), on (1)
0                                     IDEBUG:          off (0), on (1) [print debugging info]

ZONE DATA AND GRID SIZES:
16        NUMBER OF ZONES
'forebody : top'          31        31
'keel : top'              101       6
'aftbody : top'           101       31
'forebody : bot'          31        31
'ramps : bot'             55        6
'comb : bot'              101       6
'cowl : top'              101       6
'nozzle : bot'            31        6
'ramp walls : inside'     35        6
'comb wall : inside'      101       7
'nozzle wall : inside'    21        7
'aftbody : bot'           101       31
'cowl : bot'              101       6
'ramp walls : outside'    35        6
'comb wall : outside'     101       7
'nozzle wall : outside'   21        7

INPUT DATA:  (0 = degrees, 1 = m, 2 = ft, 3 = atm, 4 = dimensionless, K or kg, 5 = psf)
xl        x         xu       unit      res name
22500.    26000.    30000.    1        2500.       'altitude' - altitude (if required)
2000.     2200.     2400.0    5        200.        'q0'       - dynamic pressure (if required)
.50       1.099     1.0       4        .250        'equiv'    - equivalence ratio
1.        1.        0.0       4        -.05       'throttle' - engine throttle (if required)
6.0       6.00      8.00      4        .5          'm0'       - Mach number
-2.0      -1.0      3.00      0        .5          'AOA'      - angle of attack
6.0       4         'Mdes'      - design Mach number
1.0       0         'AOAdes'    - design angle of attack
21800.    1         'Zdes'      - design altitude
4.2672    1         'lvehicle'  - vehicle length
6.0000    0         'thforclu'  - forebody upper surface angle
5.2797    0         'thforcll'  - forebody ramp angle
0.5873    1         'lcontrol'  - control surface length
7.73      0         'th_control'- control surface deflection angle
0.9920    0         'th_expn'   - nozzle initial expansion angle
10.8958   0         'th_exit'   - nozzle exit angle
```

```
 0  0.  0.  10.   longitude
 0  90.  0.  10.  heading


VARIABLE TRACKING
 1  Number of Variables to Track
 Var          Trig Var Start   End
 -----------
 2     6       0       0       0       -1
-----------------------------------------------------------------------------

OPTIMIZATION AND CONSTRAINT PARAMETERS
-----------------------------------------------------------------------------
 1  Number of Optimization Variables
 Var    Type    Weight    Ending Trig      Target
 60  1  .001  0  -1.  0.

 2  Number of Constraint Variables
 Var    Type    Weight    Ending Trig    Start Trig        Tol       Target
 1001     1   1.00   0  -1.00   0      0.0000   1000.0000      0.0000
 1001    -1   1.00   0  -1.00   0      0.0000   1000.0000      0.0000

IO FILES
 1                            number of output files
-----------------------------------------------------------------------------
 3 5       output format, number of output variables
 1                    del(time) if >0; stride if <0
 1 11 2 30 32        variable ids (from varlist.txt)
 trajct.dat                output filename
```

Listing 8.3.8: Model.inp Output File from UCDA / Input File for UPTOP

```
GENERAL INFORMATION
 1       Number of vehicle components

 Stage/Component Linking
 num     no comps  component numbers
 1  1  1

 Stage Reference Areas
 aref           opt switch              xu          xl
 0    1.282013      0.  0.  stage(1)

 Nose Radus
 Rn       Opt Flag        -Bn     +bn
 0   6.4000001E-06   0.  100.

 VEHICLE COMPONENT PARAMETERS
 ***** Component 1 Information *****
 0    572.6713      0. 0. Dry Vehicle Mass (kilograms)

 Engine Information
 1   Total Number of Engines groups
 Eng No.  Exit Area (m^2)  tswitch  fswitch  orientation
 1  0  0  0
 0   7.8376569E-02  0  0   engine area

 Fuel Tank Information
 1  Total Number of Fuel Tanks
 Tank no.       fuel mass (kg)       stage association
 1 0    93.72025      0.  0.

 ENGINE/TANK LINKING + LIMITS
 1  Total number of links
 engine        tank       earliest on     latest off
 1  1

 DIMENSION CONVERSIONS
 1.  0  .1  1.   length
 1.  0  .1  1.   mass

 VEHICLE CONSTRAINTS
 0
 on/off var type           limit
```

8.4 Run UPTOP to Generate Optimized Trajectory for Use in TPSOPT and SMB

This section corresponds to the Step 3 in the Graphical User Interface (GUI). See Figure 8.4.1 below.

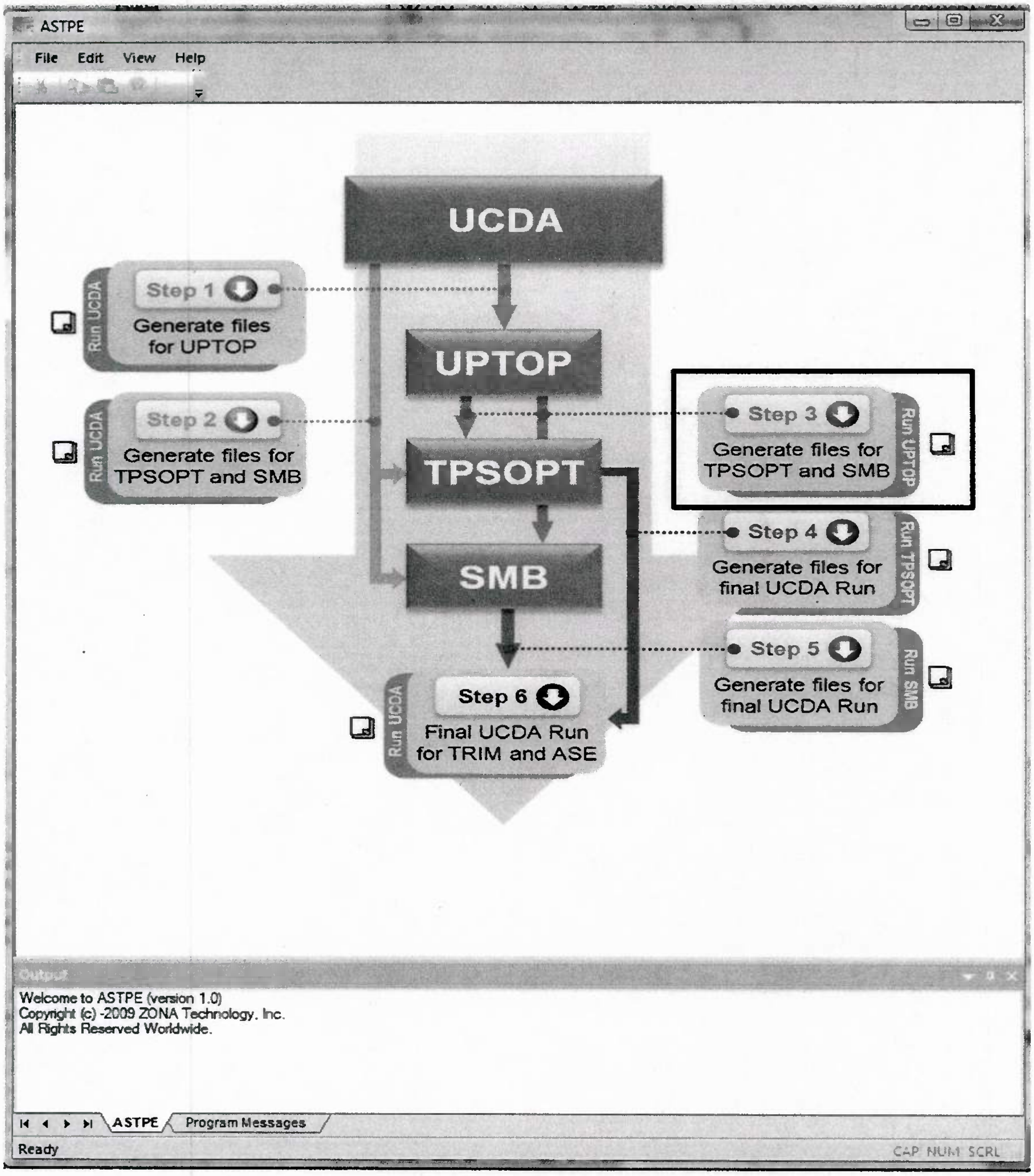


Figure 8.4.1 Section Corresponding to Step 3 of GUI

Input Files:

File Name	Type	Remarks	See Listing
des.inp	Standard input file	Required	Shown in Listing 8.4.1
params.inp	Standard input file	Required	Shown in Listing 8.4.2
traj.inp model.inp lift.tab drag.tab fuel.tab thr.tab	Input and Table files needed to generate optimized trajectory	Generated by UCDA (described in Section 8.3)	Shown in Listing 8.3.2-8.3.5, 8.3.7-8.3.8

Output Files:

File Name	Type	Remarks	See Listing
trajct.dat	Optimized trajectory as input to TPSOPT and SMB	Time, Altitude, Angle of attack and Mach number information	Shown in Listing 8.4.3
output.dat	TECPLOT format	Plotted in Fig. 8.4.2	Not Shown

Input File descriptions

des.inp: See Listing 8.4.1 for des.inp input file to UPTOP. This file specifically caters to DES optimizer. If the optimization method is fixed, this input is fixed. Thus, this file is used for all the cases in ASTPE.

params.inp: See Listing 8.4.2 for params.inp input file to UPTOP. This file contains different necessary parameters about trajectory, earth/orbit, optimization etc.

The details on each of these files are listed in the User's Manual (Sections 4.5.2 and 4.5.3).

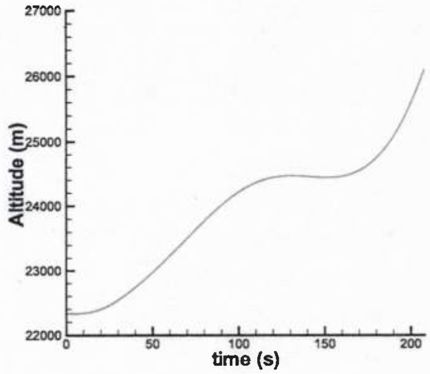
Output File descriptions

trajct.dat: See Listing 8.4.3 for this file. This file is a necessary input file for TPSOPT and SMB. Both TPSOPT and SMB need this file to compute heat flux and load respectively. The number

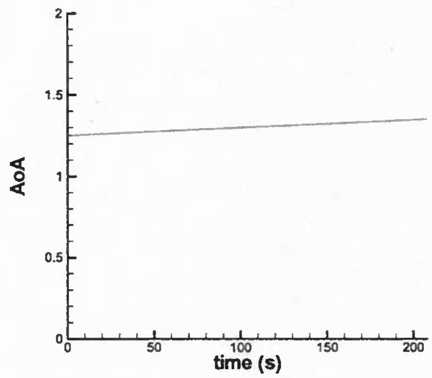
of points in trajct.dat is kept at 25 to maintain enough information about the trajectory without giving up computational efficiency.

OUTPUT.DAT: This is a TECPLOT format file and it contains optimized trajectory information. Figure 8.4.2 plots altitude, angle of attack and Mach number with respect to time using this file.

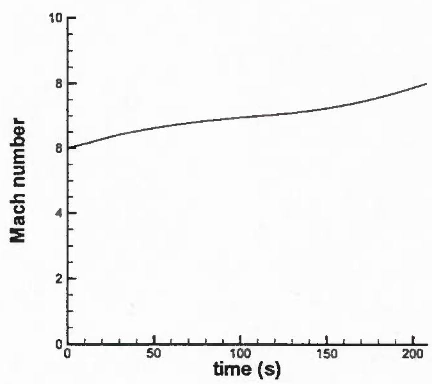
The computational time to finish this UPTOP run is approximately 10 minutes for sample SEM.



(a) Altitude



(b) AoA



(c) Mach number

Figure 8.4.2 SEM trajectory of Design Cycle 1

Listing 8.4.1: Des.inp UPTOP Input File

```
DES INPUTS

Run Control
-9                Restart (0 - new run, 1- restart)
100               Maximum Generations
0                 Convergence Criteria (# of generations without improvement)
-9        Stop when value reached

Input/Output Control
100               restart file write frequency (number of generations)
-9                screen output
1                 file output (0 - off/external, 1 - only rec. improvments, 2 - all)
0                 dvrec.out placement
10                dvrec.out flush increment

Optimization Control
0         Pareto Optimization (0 - single obj fcn, 1 - Pareto-front optimziation)
0         random number seed (0 - fcn of date, else specify exact)
50        population size
0         Localization Switch
0.                diversity threshold
0.                diversity radius

DES Operator Parameters
1         number of differential terms (1-3)
-.7       crossover probability (<0, 0-1)
-.7       mutation intensity (<0, 0-1)
-1        coefficient of complex combination (<0, 0-1)

Supplemental Optimizer
2         optimizer switch (0- none, 1- DHC, 2- DOT)
10        call frequency (< 0 = CVR, > 0 = # of generations)
0                 Maximum number of parallel calls

Mini Populations
0                 Mini-Populations switch
0
```

Listing 8.4.2: Params.inp UPTOP Input File

```
CODE PARAMETERS FILE

SWITCHES
0         Atmosphere Model (0- 1976 US Standard, 1- NRL model)
0         Rotating Earth
1         Speed of Sound (1- actual, 0-constant (sos at sea level))
1         Keep mass constant (0- constant mass, 1- fuel expended)

TRAJECTORY PARAMETERS
.1        Time Step
1000.     Maximum Time

EARTH/ORBIT INFORMATION
1         Auxillary Calculation
1         Fully resolve states
1         Calculate Ranges
0         Calculate Orbital Parameters
0         Calculate Entry Parameters
0         Full Guidance Output

OPTIMIZATION PARAMETERS
0         optimization method
1         print progress (0 - no, 1 - debug single run, -1 - debug optimization)

MAPSPACE PARAMETERS
3         number of discretization steps (0 - default=11)
1         DS value (0 - objective fcn value, 1 - true value)

OUTPUT PARAMETERS
0         screen output (0- off, 2- final output only, 1- all output)
1         record generation info (0-no, 1- record improvement,2-record all)
0         increment value for output file (0 - default=1000)
0         print input to file
1         Tecplot header

VEHICLE INFORMATION
0         vehicle model (1=hl-20, 2=F-4)
1         thrust vector alignment (0 - wind axis, 1 - vehicle nose)
```

```
CONSTANTS
9.80665    acceleration due to gravity (m/s)
6378.      radius of earth (km)
288.16     sea level temperature (K)
1.01325e5  sea level pressure (N/m^2)
1.225      sea level density (kg/m^3)

UNITS I/O
1          angles (0- radians, 1- degrees)

DEBUG
0
0
0
```

Listing 8.4.3: Trajct.dat UPTOP Output File that is used in TPSOPT and SMB

```
TRAJCT        100      10
              0.0  6.0200  22328.   1.250
              9.0  6.1200  22332.   1.250
             18.0  6.2500  22375.   1.260
             27.0  6.3800  22482.   1.260
             36.0  6.4900  22645.   1.270
             45.0  6.5800  22841.   1.270
             54.0  6.6600  23063.   1.280
             63.0  6.7300  23301.   1.280
             72.0  6.7900  23547.   1.280
             81.0  6.8500  23785.   1.290
             90.0  6.9000  24003.   1.290
             99.0  6.9500  24186.   1.300
            108.0  6.9900  24325.   1.300
            117.0  7.0300  24412.   1.310
            126.0  7.0700  24451.   1.310
            135.0  7.1200  24454.   1.310
            144.0  7.1900  24439.   1.320
            153.0  7.2600  24431.   1.320
            162.0  7.3500  24457.   1.330
            171.0  7.4500  24549.   1.330
            180.0  7.5600  24732.   1.340
            189.0  7.6900  25031.   1.340
            198.0  7.8300  25460.   1.340
            207.0  7.9800  26019.   1.350
            208.0  8.0000  26089.   1.350        TECPLOT         1209.PLT
timesp  201        0.000  45.000  90.000 135.000 180.000 208.000
```

8.5 Run UCDA to Generate Mesh for TPSOPT and SMB

This section corresponds to the Step 2 in the Graphical User Interface (GUI). See Figure 8.5.1 below.

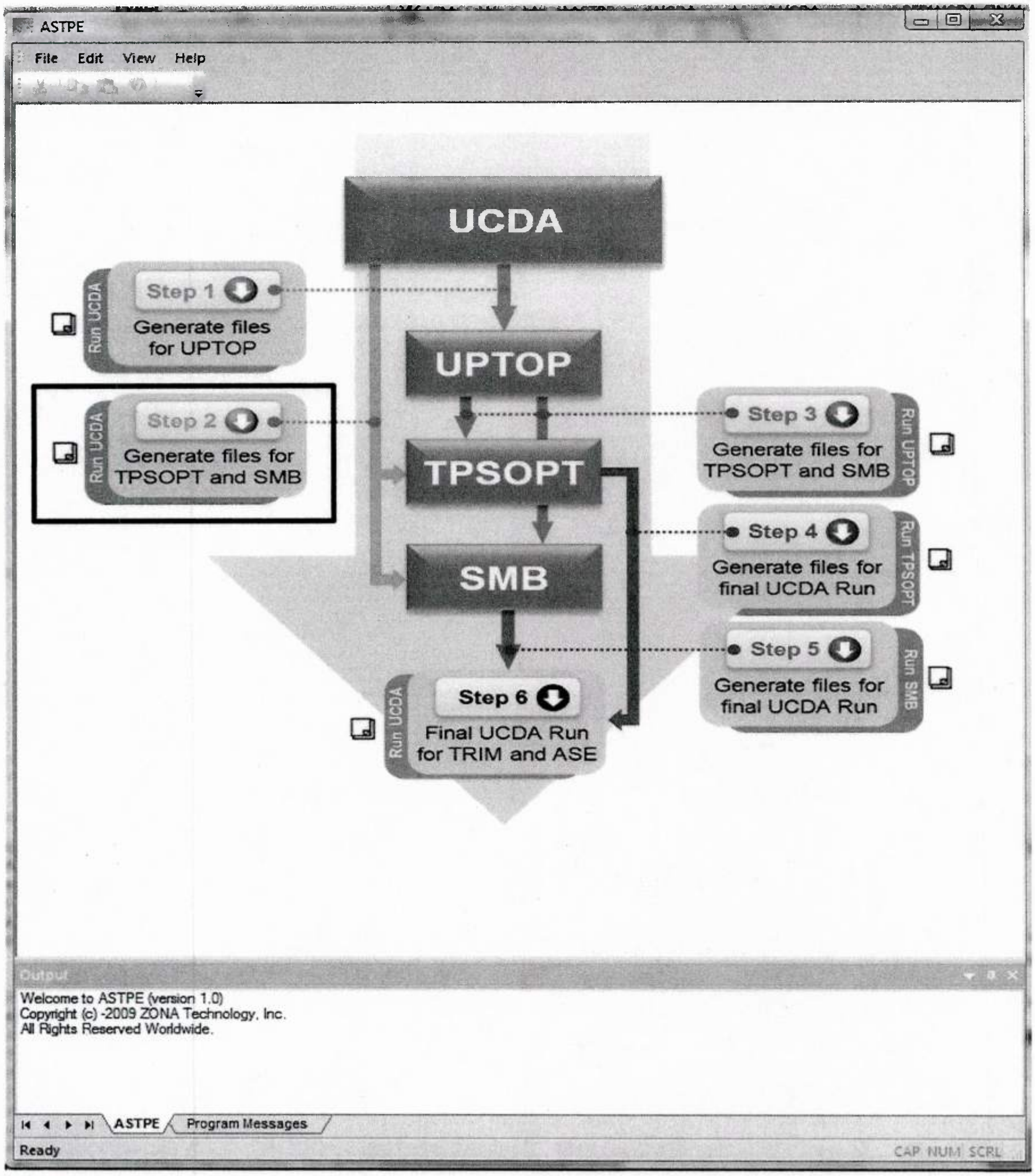


Figure 8.5.1 Section Corresponding to Step 2 of GUI

Input Files:

File Name	Type	Remarks	See Listing
vehicle.inp	Standard input file	Also look at Table 8.5.1	Shown in Listing 8.5.1
chem.bin	Engine chemistry information	Required	Shown in Listing 8.2.2

Output Files:

File Name	Type	Remarks	See Listing
geom_data.dat	unformatted	See Fig. 8.2.1	Not shown

Input File descriptions

vehicle.inp: See Listing 8.5.1 for the entire input file. The part of the input file that is used to command the code to generate mesh data for TPSOPT and SMB is shown in Table 8.5.1. It can be noted that **itps** is set to **1** in this case. This is the most important parameter to generate the mesh for TPSOPT and SMB. To run the code faster and only to output geometry information, **ideriv, itrajectory**, **itrim** are all set to **0**.

chem.bin: This file remains the same for all UCDA runs. Please see Section 8.2 for description on this file.

Output File descriptions

geom_data.dat: This file is unformatted and thus it cannot be shown. It contains information such as grid points, panel ID, normal vector, area etc. The vehicle has been shown in Figure 8.2.1. This information is read into TPSOPT and SMB to compute heat flux and load respectively.

The computational run time for generating the geometry information is about a few seconds.

Table 8.5.1: Necessary Block on Vehicle.inp to Generate Geometry Information

TEST INPUT DECK: Note - this line must be here!	
2	ialtdyn - Inlet specified alt. (0), Fixed alt. (1), or Fixed dyn. press. (2)
1	ithrottle - Run engine as a function of: (0) equivalence ratio, (1) % throttle
1	iunits - Output unit switch: SI (1) or English (2)
3	ivisc - Viscous flag: inviscid (1), laminar (2), transitional (3), turbulent (4)
1	iequiv - find max equiv ratio for choked flow: off (0) -> single run, on (1)
2	inozorder - Nozzle polynomial order: 1st (flat plate) -> 3rd
1	iheight - Height constrained vehicle: no (0) = linlet set, yes (1) = height set
0	itrajectory - Run multiple trajectory points: no (0), discrete (1), matrix (2)
0	icone - cone flow data: exact (0), curve-fit approximation (1)
1	imodel - Forebody type: WA (1), VWA (2), or VWA + cone flow (3)
0	itrim - Control surface deflection to trim the vehicle: no (0), yes (1), or optimize (2)
0	ideriv - Calculate derivatives: no (0), yes (1)
1	itps - If itps is 1, then prepare for tps and smb. ideriv and itps cannot be 1 at one time
0	ifeedback - If 1, then gets weight and Cg information from SMB and TPSOPT

Listing 8.5.1: Vehicle.inp Input File for TPS and SMB Geometry File Generation

```
TEST INPUT DECK:  Note - this line must be here!
2         ialtdyn - Inlet specified alt. (0), Fixed alt. (1), or Fixed dyn. press. (2)
1         ithrottle - Run engine as a function of: (0) equivalence ratio, (1) % throttle
1         iunits - Output unit switch: SI (1) or English (2)
3         ivisc - Viscous flag: inviscid (1), laminar (2), transitional (3), turbulent (4)
1         iequiv - find max equiv ratio for choked flow: off (0) -> single run, on (1)
2         inozorder - Nozzle polynomial order: 1st (flat plate) -> 3rd
1         iheight - Height constrained vehicle: no (0) = linlet set, yes (1) = height set
0         itrajectory - Run multiple trajectory points: no (0), discrete (1), matrix (2)
0         icone - cone flow data: exact (0), curve-fit approximation (1)
1         imodel - Forebody type: WA (1), VWA (2), or VWA + cone flow (3)
0         itrim - Control surface deflection to trim the vehicle: no (0), yes (1), or optimize (2)
0         ideriv - Calculate derivatives: no (0), yes (1)
1         itps - If itps is 1, then prepare for tps and smb. ideriv and itps cannot be 1 at one time
0         ifeedback - If 1, then gets weight and Cg information from SMB and TPSOPT

OUTPUT FILE SWITCHES AND NAMES:
1   'plot.dat'                        VEHICLEFIG:         off (0), select (1), x,y,z (2), all (3)
3 1 2 3 8 18 23       1st # -> # of variables to read, others -> vars to plot
1   'metrics.dat'                     METRICS:  off (0), on (1)
0   'cowlexit.dat'                    COWLEXIT:           off (0), on (1)
0   'moc.dat'                         NOZFIG:   off (0), P,T,M (1), all (2)
0   'offdesign.dat'                   AOA:      off (0), on (1), UPTOP input tables (2), UPTOP input files (3)
0   'scramjet.dat'                    CKENGINE: off (0), on (1)
0                                     IPRINTINLET:        off (0), all (1), results (2), all-real (3), results-real (4)
0                                     IPRINTENGINE:       off (0), on (1)
0                                     IDEBUG:           off (0), on (1) [print debugging info]

ZONE DATA AND GRID SIZES:
16        NUMBER OF ZONES
'forebody : top'             31        31
'keel : top'                 101       6
'aftbody : top'              101       31
'forebody : bot'             31        31
'ramps : bot'                55        6
'comb : bot'                 101       6
'cowl : top'                 101       6
'nozzle : bot'               31        6
'ramp walls : inside'        35        6
'comb wall : inside'         101       7
'nozzle wall : inside'       21        7
'aftbody : bot'              101       31
'cowl : bot'                 101       6
'ramp walls : outside'       35        6
'comb wall : outside'        101       7
'nozzle wall : outside'      21        7

INPUT DATA:  (0 = degrees, 1 = m, 2 = ft, 3 = atm, 4 = dimensionless, K or kg, 5 = psf)
xl        x         xu       unit      res name
22500.    26000.    30000.    1        2500.          'altitude' - altitude (if required)
2000.     2200.     2400.0    5        200.           'q0'       - dynamic pressure (if required)
.50       1.099     1.0       4        .250           'equiv'    - equivalence ratio
1.        1.        0.0       4        -.05          'throttle' - engine throttle (if required)
6.0       6.00      8.00      4         .5            'm0'       - Mach number
-2.0      -1.0      3.00      0         .5            'AOA'      - angle of attack
6.0       4         'Mdes'      - design Mach number
1.0       0         'AOAdes'    - design angle of attack
21800.    1         'Zdes'      - design altitude
4.2672    1         'lvehicle'  - vehicle length
```

```
6.0000    0        'thforclu'  - forebody upper surface angle
5.2797    0        'thforcll'  - forebody ramp angle
0.5873    1        'lcontrol'  - control surface length
7.73      0        'th_control'- control surface deflection angle
0.9920    0        'th_expn'   - nozzle initial expansion angle
10.8958   0        'th_exit'   - nozzle exit angle
0.0       4        'p_nozpoly' - % diff between nozzle designs [DON'T USE-defaulted to 1.]
1.901     1        'lcowl'     - cowl length (isolator/combustor)
.3        1        'lcowlext'  - cowl extension length (internal nozzle)
0.545     4        'p_iso'     - percent of lcowl that is isolator
.3238     1        'height'    - height of vehicle (if required)
20.0      1        'linlet'    - inlet length of vehicle (if required)
.26       1        'wengine'   - width of the engine (currently defaulted to unit width)
3.00      4        'iramps'    - number of inlet ramps in addition to the forebody
6.4012    0        'th_ramp1'  - inlet ramp 1 angle
5.2383    0        'th_ramp2'  - inlet ramp 2 angle
5.5       0        'th_ramp3'  - inlet ramp 3 angle
0.0       0        'th_ramp4'  - inlet ramp 4 angle
0.0       0        'th_ramp5'  - inlet ramp 5 angle
3.09      0        'th_div1'   - first combustor expansion angle
0.2       0        'th_div2'   - second combustor expansion angle
0.01      1        'Xinjs'       - beginning of injectors (m)
0.02      1        'Xinje'     - end of injectors (m)
0.01      1        'Lmix'      - fuel mixing length (m)
1.00      4        'eta_mix'   - fuel mixing and burning efficiency
3000.     4        'Tlimit'    - maximum engine temperature (K)
90.       0        'Thetainj'  - injector angle (degrees) [90 deg. is normal to flow]
1200.     4        'Tw'        - adiabatic wall temperature (K)
0.1527    4        'nfor'      - forebody exponent n
2.0       2        'wfor'      - forebody width
1.5       2        'lfor'      - forebody length
0.2427    4        'mfor'      - forebody exponent m
5.797     0        'thforle'   - forebody leading edge angle
21.519    0        'th_le'     - leading edge attachment angle
0.0000    4        'p_kl'      - keel-line height percentage
0.25      4        'fuelfrac'  - vehicle fuel volume fraction
0.0104    2        't_plate'   - shell plate thickness (Tungsten)
0.0       4        'mass_smb'  - mass due to Structural Modal Base (SMB) analysis
0.0       4        'mass_tps'  - mass due to Thermal Protection System (TPS) analysis
0.0       4        'mass_nose' - lumped mass at the nose to manipulate CG
```

8.6 Run TPSOPT for Optimizing the Thermal Protection System

Input Files:

File Name	Type	Remarks	See Listing
sem_tpsopt.inp	Standard input file	Required	Shown in listing 8.6.1
trajct.dat	Trajectory data generated by UPTOP	Inserted into the Standard input file sem_tpsopt.INP by the **INCLUDE** bulk data card	Shown in Listing 8.4.3
geom_data.dat	Aerodynamic mesh generated by UCDA	Imported by the ASSIGN AEROBASE executive control command	Not Shown

Output Files:

File Name	Type	Remarks	See Listing
sem_tpsopt.out	Standard output file	Print out results	Shown in Listing 8.6.2
AERO.PLT	TECPLOT file of aerodynamic mesh.	Generated by the **PLTAERO** bulk data card with ID=1	Not Shown
SEM_TPS3.PLT	TECPLOT file containing the TPS thickness of each layers on the aerodynamic panel model	Generated by the **PLTTPS** bulk data card with ID=103	Not Shown
SEM_TPS4.PLT	TECPLOT file containing the total TPS thickness on each aerodynamic panel model	Generated by the **PLTTPS** bulk data card with ID=-104	Not Shown
1209.PLT	TECPLOT file containing the heat flux at the last time step of the trajectory.	Generated by the **TRAJCT** bulk data card	Not shown
mass_tps.dat	Mass of the optimized TPS	Input file for UCDA to update the change of weight due to TPS	Shown in Listing 8.6.3

8.6.1 Descriptions of the Input File: sem_tpsopt.inp (Shown in Listing 8.6.1)

General description of Executive Control Section, Case Control Section and Bulk Data Section of TPSOPT input is given in the Users Manual (Sections 5.3 and 5.4). For sample SEM, the TPSOPT input is described here.

The aerodynamic mesh of the SEM configuration generated by UCDA is stored in the file "geom_data.dat" and imported into the TPSOPT module by the following executive control command:

ASSIGN AEROBASE = geom_data.dat

There is only one subcase defined in the case control command shown as follows:

TPSDES = 100

This case control command refers to a **TPSDES** bulk data card with ID = 100 in the Bulk Data Section. The interrelationship of all bulk data cards in the Bulk Data Section is presented in Figure 8.6.1.

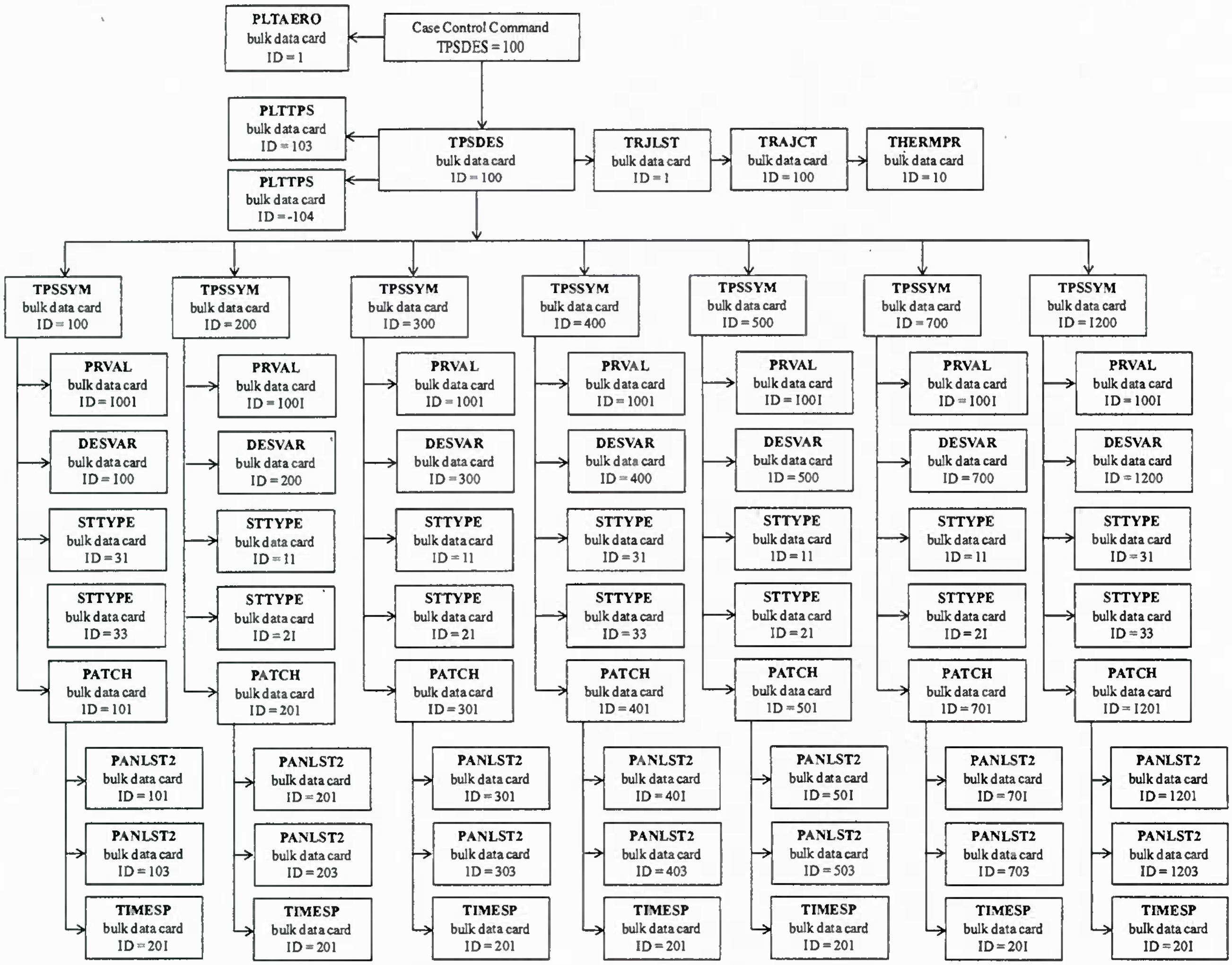


Figure 8.6.1 Interrelationship of All Bulk Data Cards for Optimizing the TPS for SEM

The aerodynamic mesh generated by UCDA and imported by the ASSIGN AEROBASE = geom_data.dat executive control command can be visualized using the TECPLOT file "AERO.PLT" that is generated by a **PLTAERO** bulk data card with ID = 1. This aerodynamic mesh is shown in Figure 8.6.2.

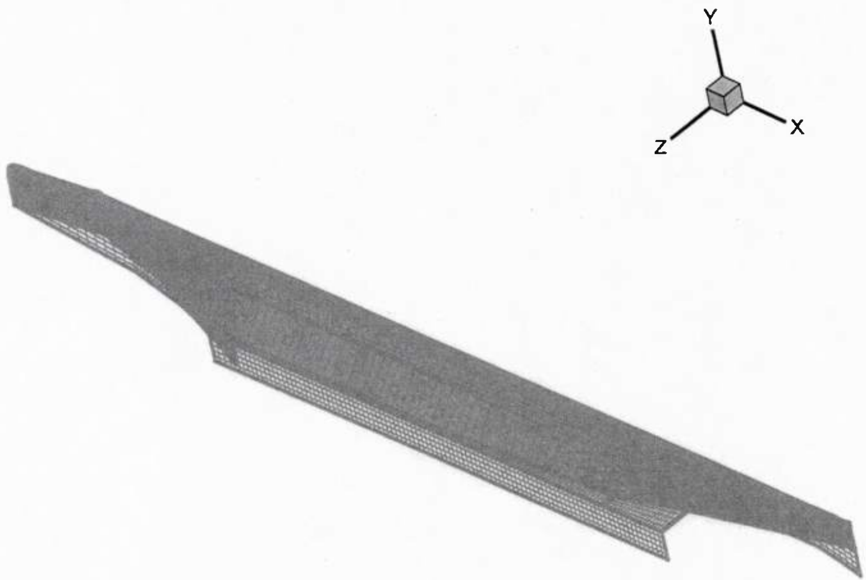


Figure 8.6.2 Visualization of Aerodynamic Mesh Using the PLTAERO bulk data card

There are 16 patches in the aerodynamic mesh but among them, only 7 patches with panel ID starting from 100001, 200001, 300001, 400001, 500001, 700001, and 1200001, respectively, are the outer surfaces and require the thermal protection system (TPS). Thus, the purpose of TPSOPT is to design the TPS system on those 7 patches for minimum TPS weight while satisfying the temperature constraints of each TPS layer as well as the load-carried structure. These temperature constraints are computed by integrating the heat flux on the outer surfaces along the trajectory generated by UPTOP. This trajectory is provided in the file "trajct.dat" in which a **TRAJCT** bulk data card with ID = 100 and a **TIMESP** bulk data card with ID = 201 are stored. These two bulk data cards are automatically inserted into the bulk data section by the **INCLUDE** bulk data card shown as follows:

```
INCLUDE    trajct.dat
```

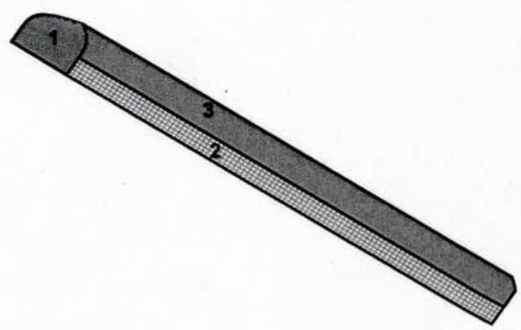
Note that the **TRAJCT** bulk data card with ID = 100 is referred to by a **TRJLST** bulk data card with ID = 1 that is activated by the **TPSDES** bulk data card with ID = 100. The parameters for computing the heat flux by the aeroheating analysis are defined in a **THERMPR** bulk data card with ID = 10 that is referred to by the **TRAJCT** bulk data card with ID = 100.

In order to design the minimum TPS weight on those 7 patches, 7 **TPSSYM** bulk data cards with ID = 100, 200, 300, 400, 500, 700, and 1200 are specified that are all referred to by the **TPSDES** bulk data card with ID = 100. Each **TPSSYM** bulk data card refers to a **PRVAL** bulk data card, a **DESVAR** bulk data card, a **PATCH** bulk data card and two **PANLST2** bulk data cards. The **PRVAL** bulk data card with ID = 1001 that is referred to by all the 7 **TPSSYM** bulk data cards defines the parameters for the transient thermal analysis. The **PATCH** bulk data card first refers to a **PANLST2** bulk data card to list the identification numbers of the panels that belong to a patch in the aerodynamic mesh. Then it refers to another **PANLST2** bulk data card to define a set of so-called "hot panels" on which the temperature constraints of the TPS is imposed by listing the identification numbers of those hot panels. Note that those hot panels must be a subset of the panels of the patch.

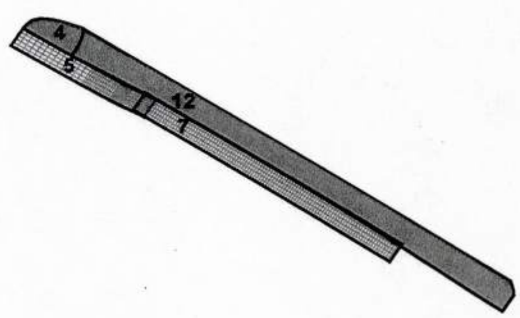
The temperature constraints are evaluated at all layers of the TPS located on those hot panels and are computed at a set of time steps defined by the **TIMESP** bulk data card with ID = 201. Thus, the total number of the temperature constraints is product of the number of layers of the TPS, the number of the hot panels, and the number of time steps listed in the **TIMESP** bulk data card. This is the reason why only 6 time steps in the **TIMESP** are selected from those 25 time steps in the **TRAJCT** bulk data card. Otherwise, if all those 25 time steps listed in the **TRAJCT** bulk data card are used to evaluate the temperature constraints, the number of temperature constraints would be too many and might require the amount of computer memory beyond the available memory in the computer.

Seven **PATCH** bulk data cards with ID = 101, 201, 301, 401, 501, 701, and 1201 that are referred to by those 7 **TPSSYM** bulk data cards respectively, are used to define the panels on

those 7 outer surface patches in the aerodynamic mesh by specifying 7 **PANLST2** bulk data cards with ID = 101, 201, 301, 401, 501, 701 and 1201. The hot panels on those 7 patches are defined by another 7 **PANLST2** bulk data cards with ID = 103, 203, 303, 403, 503, 703, and 1203. The identification numbers of those panels on the 7 patches are presented in Figure 8.6.3.



(a)



(b)

Figure 8.6.3 Panel Identification Numbers on the 7 Patches with TPS

The correspondences between 7 patches and the zones shown in Figure 8.2.1 are:

patch 1: forebody top

patch 2: keel top

patch 3: aftbody top

patch 4: forebody bottom

patch 5: ramp bottom

patch 7: cowl top

patch 12: aftbody bottom

Patches 1, 4 and 12 with panel ID starting from 100001, 400001 and 1200001, respectively, are potentially exposed to the high aeroheating environment. This suggests that in order to achieve a minimum weight design of the TPS, different TPS concepts and materials from the rest of the patches be employed for those 3 patches. This TPS consists of two TPS layers and is defined in the **TPSSYM** bulk data cards with ID = 100, 400 and 1200 in which the top layer is defined by a **STTYPE** bulk data card with ID = 31 and the bottom layer is defined by a **STTYPE** bulk data card with ID = 33. The **STTYPE** bulk data card with ID = 31 defines a Slab TPS structure made by ZIRCONIA FIBERS with initial thickness = 0.1 m whereas the STTYPE bulk data card with ID = 33 defines a Slab structure made by a HEAT SINK with thickness = 0.2 m. This HEAT SINK is n virtual material with a very high heat capacity to represent an active cooling concept that absorbs the heat by circling the fuel. The thickness of the ZIRCONIA FIBERS is subjected to the design for minimum weight with the design variable being defined by a **DESVAR** bulk data card whereas the thickness of the HEAT SINK is kept to be constant at 0.2 m. Three **DESVAR** bulk data cards with ID = 100, 400, and 1200 are specified that are referred to by the entry DESVAR1 of the three **TPSSYM** bulk data cards with ID = 100, 400 and 1200, respectively. A minimum and maximum thickness of 0.0002 m and 10.0 m for the ZIRCORNIA FIBERS is also specified in these **TPSSYM** bulk data cards. Note that the entry DESVAR2 of these three **TPSSYM** bulk data cards is blank to indicate that the bottom layer; i.e. the thickness

of the HEAT SINK, is not subjected to design and remains unaltered. The purpose of the **DESVAR** bulk data card is to define a curvilinear coordinates over the patch on which a set of shape functions can be formulated to represent the thickness distribution of the ZIRCONIA FIBERS on this patch. Thus, the actual design variables controlled by the optimizer are the unknown coefficients of those shape functions and are not the thickness of the ZIRCORNIA FIBERS on each panel. Using these shape functions, the number of design variables can be greatly reduced and the thickness distribution of the optimized TPS is ensured to be smooth for the ease of fabrication. This curvilinear coordinates is defined by selecting a set of M by N panels on the patch. A 2 by 2 panels is defines by the **DESVAR** bulk data cards with ID = 100 and 400 and a 3 by 3 panels is defined by the **DESVAR** bulk data card with ID = 1200. (Please refer to Users Manual Section 5.4, TPSOPT Bulk Data Section, for more information about DESVAR bulk data card.)

The TPS on the rest of 4 patches defined by the four **TPSSYM** bulk data cards with ID = 200, 300, 500 and 700 is also a two-layer TPS. The top layer is a Slab structure made by CRI-II and is defined by a **STTYPE** bulk data card with ID = 11 whereas the bottom layer is a thin skin made by RTV-560 and is defined by a **STTYPE** bulk data card with ID = 21. The top layer is subjected to design with initial thickness of 0.1 m and minimum thickness and maximum thickness of 0.002 m and 10.0 m, respectively, and the bottom layer is kept to be 2.45×10^{-5} m. Four **DESVAR** bulk data cards with ID = 200, 300, 500 and 700 that are referred by the **TPSSYM** bulk data cards with ID = 200, 300, 500 and 700, respectively, are specified to select an M by N panels for defining the curvilinear coordinates on their respective patches. A set of 2 by 3 panels is defined by the **DESVAR** bulk data cards with ID = 200, 500 and 700 and a set of 3 by 3 panels by the **DESVAR** bulk data card with ID = 300. (Please refer to Users Manual Section 5.4, TPSOPT Bulk Data Section, for more information about DESVAR bulk data card.)

In order to visualize to optimized TPS thickness distribution, two **PLTTPS** bulk data cards with ID = 103 and = -104 are employed that generate two TECPLOT files called "SEM_TPS3.PLT" and "SEM_TPS4.PLT", respectively where the first contains the thickness of each TPS layer and the maximum temperature on each panel and the latter contains the total thickness of the TPS. In addition, the heat flux at a time step in the trajectory can be also outputted in a TECPLOT file by

specifying a file name in the **TRAJCT** bulk data card. A TECPLOT file called "1209.PLT' is generated to display the heat flux at the last time step of the trajectory.

The final optimized averaged TPS thickness of each layer of patched 100, 200, 300, 400, 500, 700, and 1200 are shown in Figures 8.6.4, 8.6.5, 8.6.6, 8.6.7, 8.6.8, 8.6.9 and 8.6.10. The masses of those 7 TPS are 3.07170152E-03, 1.65916653E+00, 3.89700886E+00, 1.46587057E-03, 7.15747357E-01, 2.09356866E+00, and 1.85629520E-02 KG, respectively; giving a total mass of the entire TPS of 15.66 KG (both sides). This total mass along with the sum of the product of TPS mass on each panel and the location of the panel is stored in a file called "mass_tps.dat" that is shown in Listing 8.6.3. This file will be an input file of UCDA to include the TPS weight in the total vehicle weight for the next design cycle.

```
                 OPTIMAL STRUCTURES OF TPS FOR PATCH =      100
                         (WITH AVERAGE THICKNESS)
============================================================   -----
                                                                 i
                         ZIRCONIA FIBERS      slab             0.00066 FT    2278.6 F
                                                                 i
============================================================   -----
                                                                 i
                         HEAT SINK            slab             0.65617 FT    2177.0 F
                                                                 i
============================================================   -----
```

Figure 8.6.4 Optimized Averaged TPS Thickness of Patch 100

```
                 OPTIMAL STRUCTURES OF TPS FOR PATCH =      200
                         (WITH AVERAGE THICKNESS)
============================================================   -----
                                                                 i
                         CRI-I   2.0          slab             0.05911 FT    2117.2 F
                                                                 i
============================================================   -----
                         RTV-560              thin skin        0.00066 FT     548.5 F
============================================================   -----
```

Figure 8.6.5 Optimized Averaged TPS Thickness of Patch 200

```
                 OPTIMAL STRUCTURES OF TPS FOR PATCH =      300
                         (WITH AVERAGE THICKNESS)
============================================================   -----
                                                                 i
                         CRI-I   2.0          slab             0.07074 FT    2290.3 F
                                                                 i
============================================================   -----
                         RTV-560              thin skin        0.00066 FT     546.0 F
============================================================   -----
```

Figure 8.6.6 Optimized Averaged TPS Thickness of Patch 300

```
              OPTIMAL STRUCTURES OF TPS FOR PATCH =     400
                     (WITH AVERAGE THICKNESS)
=============================================================   -----
                                                                  i
                    ZIRCONIA FIBERS      slab                   0.00066 FT    2406.5 F
                                                                  i
=============================================================   -----
                                                                  i
                    HEAT SINK            slab                   0.65617 FT    2299.5 F
                                                                  i
=============================================================   -----
```

Figure 8.6.7 Optimized Averaged TPS Thickness of Patch 400

```
              OPTIMAL STRUCTURES OF TPS FOR PATCH =     500
                     (WITH AVERAGE THICKNESS)
=============================================================   -----
                                                                  i
                    ZIRCONIA FIBERS      slab                   0.12422 FT    2670.4 F
                                                                  i
=============================================================   -----
                    RTV-560              thin skin              0.00066 FT     548.0 F
=============================================================   -----
```

Figure 8.6.8 Optimized Averaged TPS Thickness of Patch 500

```
              OPTIMAL STRUCTURES OF TPS FOR PATCH =    700
                     (WITH AVERAGE THICKNESS)
=============================================================   -----
                                                                  i
                 CRI-I  2.0          slab                    0.076302 FT   2128.3 F
                                                                  i
=============================================================   -----
                    RTV-560              thin skin              0.00066 FT     548.0 F
=============================================================   -----
```

Figure 8.6.9 Optimized Averaged TPS Thickness of Patch 700

```
              OPTIMAL STRUCTURES OF TPS FOR PATCH =   1200
                     (WITH AVERAGE THICKNESS)
=============================================================   -----
                                                                  i
                    ZIRCONIA FIBERS      slab                   0.00066 FT    2743.2 F
                                                                  i
=============================================================   -----
                                                                  i
                    HEAT SINK            slab                   0.65617 FT    2613.3 F
                                                                  i
=============================================================   -----
```

Figure 8.6.10 Optimized averaged TPS thickness of patch 1200

Using the file "SEM_TPS4.PLT", the total thickness contour of the TPS and the maximum temperature distribution are depicted in Figures 8.6.11 and 8.6.12, respectively. The heat flux at the last time step of the trajectory is shown in Figure 8.6.13.

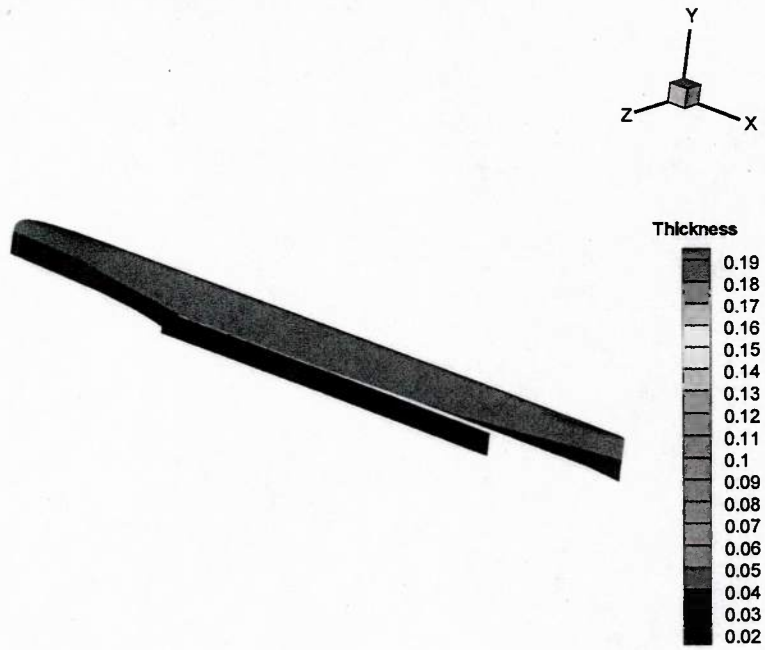


Figure 8.6.11 Thickness Contour of the Optimized TPS

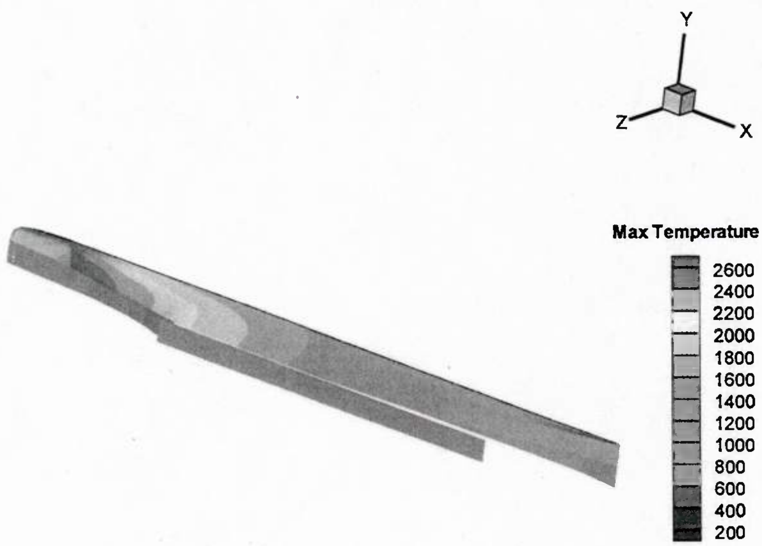


Figure 8.6.12 Temperature Contour of the Optimized TPS

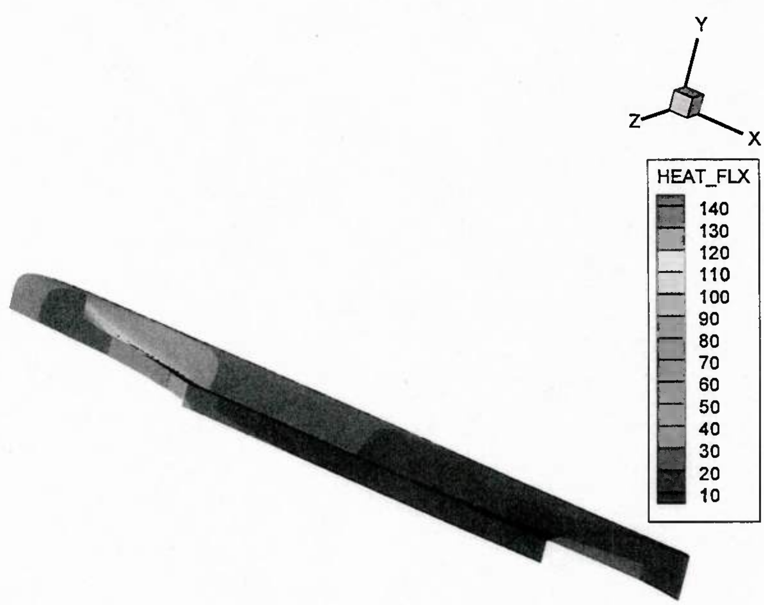


Figure 8.6.13 Heat Flux at the Last Time Step of the Trajectory

Listing 8.6.1 Sample Input File: sem_tpsopt.inp

```
ASSIGN AEROBASE=geom_data.dat,PRINT=1
CEND
TITLE=SEM CONFIGURATION
ECHO=SORT
SUBCASE =1
   TPSDES=100
BEGIN BULK
INCLUDE 'trajct.dat'
$2345678123456781234567812345678123456781234567812345678123456781234567812345678
PLATAERO 1                                      tecplot aero.plt
$...1..|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|...10..|
$            SETID  TPSDES  TPSSYM    FORM      FILENM
PLTTPS        103    100       ALL TECPLOT    SEM_TPS3.PLT  -30.00
PLTTPS       -104    100       ALL TECPLOT    SEM_TPS4.PLT  -30.00
TPSDES  100     1       1
        100     200     300     400     500     700     1200
TRJLST  1
        100
THERMPR 10      100.F   yes     2       0       0.8
$2345678123456781234567812345678123456781234567812345678123456781234567812345678
TPSSYS  100     101     2       1001
        100     31      .0002   10.
                33      .0002   90.
PATCH   101     101     103     NO              201
PANLST2 101     100001  100001  thru    100900
PANLST2 103     100001  100001  100030  100871  100900
DESVAR  100     2       2
        100001  100030
        100871  100900
$TIMESP  201     0.      6.3     12.6    18.9    25.2    31.56   37.88
$        44.21   50.5    56.86   63.2    69.5    75.87   82.2    88.55
$        94.9    101.2   107.6   113.9   120.3   126.6
$2345678123456781234567812345678123456781234567812345678123456781234567812345678
TPSSYM  200     201     2       1001
        200     11      .0002   10.
                21      .0002   10.
DESVAR  200     2       3
        200001  200100
        200201  200300
        200401  200500
PATCH   201     201     203     NO              201
PANLST2 201     200001  200001  thru    200500
PANLST2 203     200001  200001  200100  200201  200300  200401  200500
$2345678123456781234567812345678123456781234567812345678123456781234567812345678
TPSSYM  300     301     2       1001
        300     11      .0002   10.
                21      .0002   10.
DESVAR  300     3       3
        300001  301501  302901
        300050  301550  302950
        300100  301600  303000
PATCH   301     301     303     NO              201
PANLST2 301     300001  300001  thru    303000
PANLST2 302     300001  300001  301501  302901  300050  301550  302950
        300100  301600  303000
PANLST2 303     300001  300001  300025  300050  300075  300100  301501
        301525  301550  301575  301600  302901  302925  302950  302975
        303000
$2345678123456781234567812345678123456781234567812345678123456781234567812345678
TPSSYM  400     401     2       1001
        400     31      .0002   10.
                33      .0002   90.
PATCH   401     401     403     NO              201
PANLST2 401     400001  400001  thru    400900
PANLST2 403     400001  400001  400030  400871  400900
DESVAR  400     2       2
        400001  400030
        400871  400900
$2345678123456781234567812345678123456781234567812345678123456781234567812345678
TPSSYM  500     501     2       1001
        500     31      .0002   10.
                21      .0002   10.
PATCH   501     501     503     NO               201
PANLST2 501     500001  500001  thru    500270
PANLST2 503     500001  500001  500054  500109   500162   500217  500270
DESVAR  500     2       3
        500001  500054
        500109  500162
        500217  500270
$2345678123456781234567812345678123456781234567812345678123456781234567812345678
TPSSYM  700     701     2       1001
        700     11      .0002   10.
                21      .0002   10.
PATCH   701     701     703     NO              201
PANLST2 701     700001  700001  thru    700500
PANLST2 703     700001  700001  700100  700201  700300  700401  700500
DESVAR  700     2       3
```

```
        700001  700100
        700201  700300
        700401  700500
$2345678123456781234567812345678123456781234567812345678123456781234567812345678
$2345678123456781234567812345678123456781234567812345678123456781234567812345678
TPSSYM  1200    1201    2       1001
        1200    31      .0002   10.
                33      .0002   90.
PATCH   1201    1201    1203    NO              201
PANLST2 1201    1200001 1200001 thru    1203000
PANLST2 1203    1200001 1200001 1200025 1200050 1200075 1200100 1201501
        1201525 1201550 1201575 1201600 1202901 1202925 1202950 1202975
        1203000
$PANLST2 1203    1200001 1200001 1200050 1200075 1200100 1201501  1201550
$        1201575 1201600 1202901 1202950 1203000
DESVAR  1200    3       3
        1200001 1201501 1202901
        1200050 1201550 1202950
        1200100 1201600 1203000
$2345678123456781234567812345678123456781234567812345678123456781234567812345678
$...1..|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|...10..|
PRVAL       1001        90000000
                                       0
STTYPE  11      1       315
        0.100
STTYPE  21      6       245
        2.45e-5
STTYPE  31      1       251
        0.100
STTYPE  41      1       221
        0.100
STTYPE  2       1       266
        0.001
STTYPE  3       1       260
        0.001
STTYPE  4       1       266
        0.001
STTYPE  5       1       245
        0.001
STTYPE  6       1       101
        0.010
STTYPE  33      1       701
        0.200
STTYPE  34      1       501
        0.200
STTYPE  35      1       502
        0.200
STTYPE  36      1       309
        0.200
$2345678123456781234567812345678123456781234567812345678123456781234567812345678
ENDDATA
```

Listing 8.6.2 Sample Output File: sem_tpsopt.out

```
                    E X E C U T I V E   C O N T R O L   S U M M A R Y

|...1...|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|..10...|

ASSIGN AEROBASE=geom_data.dat,PRINT=1

CEND

                         C A S E   C O N T R O L   S U M M A R Y
```

```
                    S I N G L E   P R E C I S I O N   C O M P U T A T I O N

              M A X I M U M   A L L O C A B L E   M E M O R Y  = 800  M E G A B Y T E S

          |...1...|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|..10...|

          TITLE=SEM CONFIGURATION
          ECHO=SORT
          SUBCASE =1
          TPSDES=100
          BEGIN BULK

                              S O R T E D   B U L K   D A T A   E C H O
CARD
COUNT     |...1...|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|..10...|

    1 -   DESVAR  100     2       2
    2 -           100001  100030
    3 -           100871  100900
    4 -   DESVAR  200     2       3
    5 -           200001  200100
    6 -           200201  200300
    7 -           200401  200500
    8 -   DESVAR  300     3       3
    9 -           300001  301501  302901
   10 -           300050  301550  302950
   11 -           300100  301600  303000
   12 -   DESVAR  400     2       2
   13 -           400001  400030
   14 -           400871  400900
   15 -   DESVAR  500     2       3
   16 -           500001  500054
   17 -           500109  500162
```

```
        500217  500270
DESVAR  700     2       3
        700001  700100
        700201  700300
        700401  700500
DESVAR  1200    3       3
        1200001 1201501 1202901
        1200050 1201550 1202950
        1200100 1201600 1203000
PANLST2 101     100001  100001  THRU    100900
PANLST2 103     100001  100001  100030  100871  100900
PANLST2 201     200001  200001  THRU    200500
PANLST2 203     200001  200001  200100  200201  200300  200401  200500
PANLST2 301     300001  300001  THRU    303000
PANLST2 302     300001  300001  301501  302901  300050  301550  302950
        300100  301600  303000
PANLST2 303     300001  300001  300025  300050  300075  300100  301501
        301525  301550  301575  301600  302901  302925  302950  302975
        303000
PANLST2 401     400001  400001  THRU    400900
PANLST2 403     400001  400001  400030  400871  400900
PANLST2 501     500001  500001  THRU    500270
PANLST2 503     500001  500001  500054  500109  500162  500217  500270
PANLST2 701     700001  700001  THRU    700500
PANLST2 703     700001  700001  700100  700201  700300  700401  700500
PANLST2 1201    1200001 1200001 THRU    1203000
PANLST2 1203    1200001 1200001 1200025 1200050 1200075 1200100 1201501
        1201525 1201550 1201575 1201600 1202901 1202925 1202950 1202975
        1203000
PATCH   101     101     103     NO              201
PATCH   201     201     203     NO              201
PATCH   301     301     303     NO              201
PATCH   401     401     403     NO              201
PATCH   501     501     503     NO              201
PATCH   701     701     703     NO              201
PATCH   1201    1201    1203    NO              201
```

```
PLTAERO 1                                TECPLOT AERO.PLT
PLTTPS  -104     100     ALL     TECPLOT SEM_T   PS4.PLT -30.00
PLTTPS  103      100     ALL     TECPLOT SEM_T   PS3.PLT -30.00
PRVAL   1001             90000000
                                 0
STTYPE  2        1       266
        0.001
STTYPE  3        1       260
        0.001
STTYPE  4        1       266
        0.001
STTYPE  5        1       245
        0.001
STTYPE  6        1       101
        0.010
STTYPE  11       1       315
        0.100
STTYPE  21       6       245
        2.45E-5
STTYPE  31       1       251
        0.100
STTYPE  33       1       701
        0.200
STTYPE  34       1       501
        0.200
STTYPE  35       1       502
        0.200
STTYPE  36       1       309
        0.200
STTYPE  41       1       221
        0.100
THERMPR 10       100.F   YES     2       0       0.8
TIMESP  201      0.000   45.000  90.000  135.000 180.000 208.000
TPSDES  100      1       1
        100      200     300     400     500     700     1200
TPSSYM  100      101     2       1001
```

```
        100     31      .0002   10.
                33      .0002   90.
TPSSYM  200     201     2       1001
        200     11      .0002   10.
                21      .0002   10.
TPSSYM  300     301     2       1001
        300     11      .0002   10.
                21      .0002   10.
TPSSYM  400     401     2       1001
        400     31      .0002   10.
                33      .0002   90.
TPSSYM  500     501     2       1001
        500     31      .0002   10.
                21      .0002   10.
TPSSYM  700     701     2       1001
        700     11      .0002   10.
                21      .0002   10.
TPSSYM  1200    1201    2       1001
        1200    31      .0002   10.
                33      .0002   90.
TRAJCT  100     10
        0.0     6.0200  22328.  1.250
        9.0     6.1200  22332.  1.250
        18.0    6.2500  22375.  1.260
        27.0    6.3800  22482.  1.260
        36.0    6.4900  22645.  1.270
        45.0    6.5800  22841.  1.270
        54.0    6.6600  23063.  1.280
        63.0    6.7300  23301.  1.280
        72.0    6.7900  23547.  1.280
        81.0    6.8500  23785.  1.290
        90.0    6.9000  24003.  1.290
        99.0    6.9500  24186.  1.300
        108.0   6.9900  24325.  1.300
        117.0   7.0300  24412.  1.310
        126.0   7.0700  24451.  1.310
```

```
127 -            135.0  7.1200  24454.  1.310

128 -            144.0  7.1900  24439.  1.320

129 -            153.0  7.2600  24431.  1.320

130 -            162.0  7.3500  24457.  1.330

131 -            171.0  7.4500  24549.  1.330

132 -            180.0  7.5600  24732.  1.340

133 -            189.0  7.6900  25031.  1.340

134 -            198.0  7.8300  25460.  1.340

135 -            207.0  7.9800  26019.  1.350

136 -            208.0  8.0000  26089.  1.350          TECPLOT         1209.PLT

137 -      TRJLST  1

138 -            100

139 -      ENDDATA
```

```
****************************************
*                                      *
*      SUBCASE        =        1       *
*      DISCIPLINE     = TPSDES         *
*      BULK ENTRY ID  =      100       *
*                                      *
****************************************
```

```
                OPTIMIZATION SYSTEM FOR TPSSYM =    100

 TOTAL NUMBER OF DESIGN VARIABLES =     4

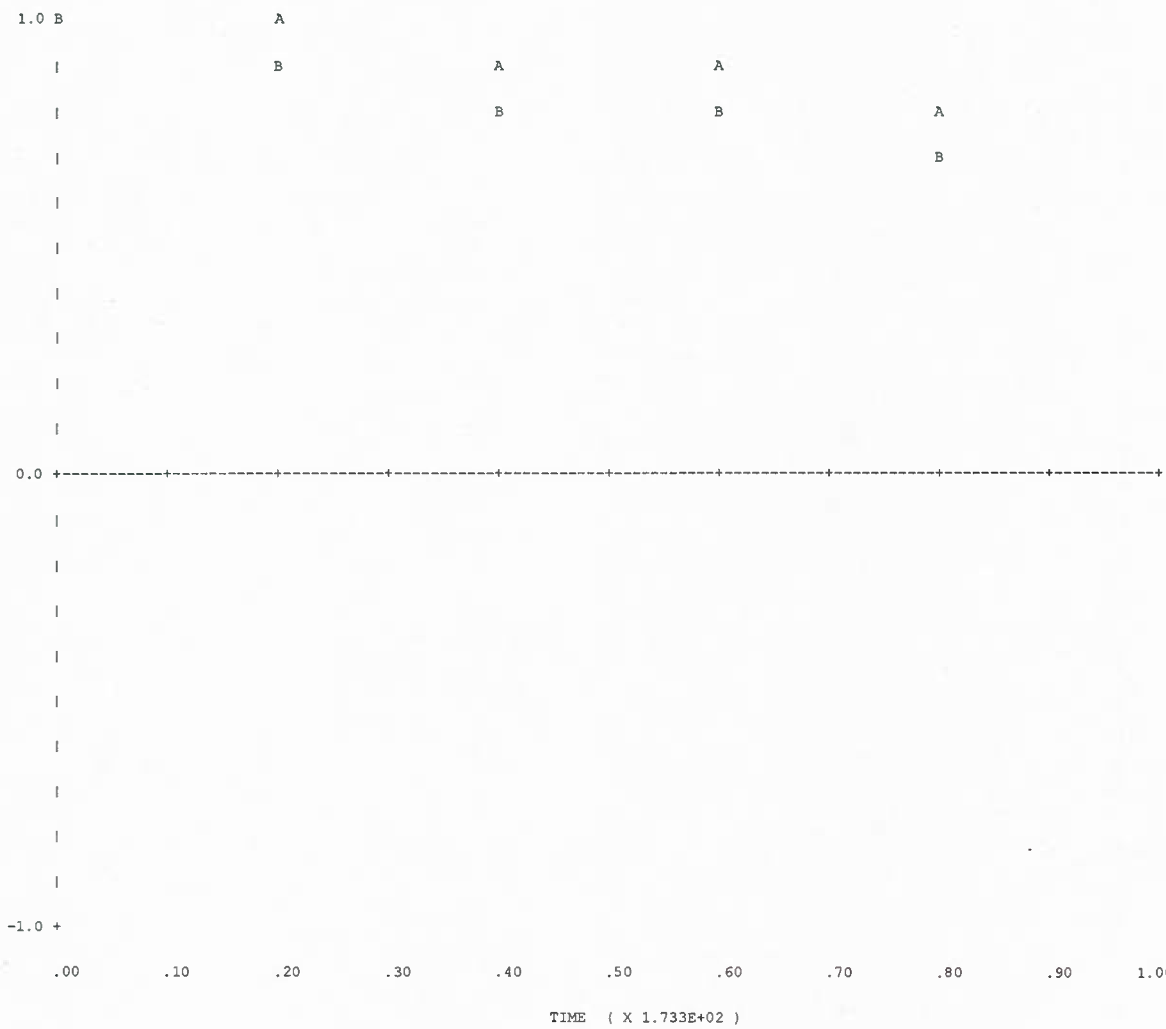
 TOTAL NUMBER OF CONSTRAINS       = 1840

 TOTAL NUMBER OF TEMP. CONSTRAINS =   48

 TOTAL NUMBER OF TEMP. PRINTOUTS  =    6


MAXIMUM TEMPERATURE OF EACH LAYER VS OUTPUT TIMES

    X   0.2279E+04
```



MAXIMUM TEMPERATURE OF EVERY LAYER

LAYER:	1	2
Tmax:	3000.33	8540.33
Optv:	2278.59	2176.96

VALUES OF DESIGN VARIABLES :

LAYER	DEV01	DEV02	DEV03	DEV04
1	0.00020	0.00020	0.00020	0.00020

THE ORIGINAL OBJECTIVE FUNCTION = 1771.6535645

```
THE RATIO OF OPTIMAL OBJECTIVE FUNCTION =   0.0020000


THE TOTAL OPTIMAL WEIGHT = 3.07170152E-03


            OPTIMAL STRUCTURES OF TPS FOR PATCH =     100

                  (WITH AVERAGE THICKNESS)

===========================================================  -----

                                                               i

                  ZIRCONIA FIBERS      slab                0.00066 FT   2278.6 F

                                                               i

===========================================================  -----

                                                               i

                  HEAT SINK            slab                0.65617 FT   2177.0 F

                                                               i

===========================================================  -----



        THICKNESS AND TEMPERATURE OF LAYERS FOR PATCH =     100


  PANEL  LAYER01            LAYER02

 100001  0.00020  2278.59  0.20000  2176.96

 100002  0.00020  2266.32  0.20000  2215.62

.................................................................

.................................................................

.................................................................

 100899  0.00020   100.00  0.20000   100.00

 100900  0.00020   100.00  0.20000   100.00



                OPTIMIZATION SYSTEM FOR TPSSYM =   200



TOTAL NUMBER OF DESIGN VARIABLES =    6

TOTAL NUMBER OF CONSTRAINS        = 1060

TOTAL NUMBER OF TEMP. CONSTRAINS =   72
```

TOTAL NUMBER OF TEMP. PRINTOUTS =   6

WARNING: MODIFICATION EXEEDS ALLOWED VALUE

MAXIMUM TEMPERATURE OF EACH LAYER VS OUTPUT TIMES

```
   X   0.2117E+04

 1.0 A                       A
     I                                               A                       A                       A
     I
     I
     I
     I
     I
     B
     I                       B                       B
     I                                                                       B
 0.0 +-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------B-----------+-----------+
     I
     I
     I
     I
     I
     I
     I
     I
     I
-1.0 +
     .00         .10         .20         .30         .40         .50         .60         .70         .80         .90        1.00
                                                         TIME  ( X 1.733E+02 )
```

MAXIMUM TEMPERATURE OF EVERY LAYER

LAYER:	1	2
Tmax:	2400.33	550.33
Optv:	2117.20	548.45

VALUES OF DESIGN VARIABLES :

LAYER	DEV01	DEV02	DEV03	DEV04	DEV05	DEV06
1	0.02243	0.01363	0.02241	0.01362	0.02240	0.01361

THE ORIGINAL OBJECTIVE FUNCTION = 1742.1259766

THE RATIO OF OPTIMAL OBJECTIVE FUNCTION = 0.1799643

THE TOTAL OPTIMAL WEIGHT = 1.65916653E+00

OPTIMAL STRUCTURES OF TPS FOR PATCH = 200

(WITH AVERAGE THICKNESS)

```
==========================================================   -----
                                                                i
                    CRI-I  2.0          slab                 0.05911 FT   2117.2 F
                                                                i
==========================================================   -----
                    RTV-560             thin skin            0.00066 FT    548.5 F
==========================================================   -----
```

THICKNESS AND TEMPERATURE OF LAYERS FOR PATCH = 200

PANEL	LAYER01		LAYER02	
200001	0.02243	2116.93	0.00002	550.33
200002	0.02234	2108.23	0.00002	550.33
....				
....				
....				
200499	0.01370	1270.89	0.00002	550.33
200500	0.01361	1261.99	0.00002	550.33

OPTIMIZATION SYSTEM FOR TPSSYM = 300

```
TOTAL NUMBER OF DESIGN VARIABLES =    9

TOTAL NUMBER OF CONSTRAINS       = 6162

TOTAL NUMBER OF TEMP. CONSTRAINS =  180

TOTAL NUMBER OF TEMP. PRINTOUTS  =    6

WARNING: MODIFICATION EXEEDS ALLOWED VALUE
```

```
MAXIMUM TEMPERATURE OF EACH LAYER VS OUTPUT TIMES

    X   0.2290E+04

  1.0 A                       A
      I                                               A                       A
      I                                                                                               A
      I
      I
      I
      I
      I
      B                       B
      I                                               B                       B
  0.0 +-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------B-----------+-----------+
      I
      I
      I
      I
      I
      I
      I
      I
      I
 -1.0 +
      .00         .10         .20         .30         .40         .50         .60         .70         .80         .90        1.00

                                                  TIME   ( X 1.733E+02 )
```

MAXIMUM TEMPERATURE OF EVERY LAYER

LAYER:	1	2
Tmax:	2400.33	550.33
Optv:	2290.35	545.99

VALUES OF DESIGN VARIABLES :

LAYER	DEV01	DEV02	DEV03	DEV04	DEV05	DEV06	DEV07	DEV08	DEV09
1	0.02132	0.02140	0.02248	0.02163	0.02165	0.02176	0.02116	0.02114	0.02116

THE ORIGINAL OBJECTIVE FUNCTION = 10452.7675781

THE RATIO OF OPTIMAL OBJECTIVE FUNCTION = 0.2155271

THE TOTAL OPTIMAL WEIGHT = 3.89700886E+00

OPTIMAL STRUCTURES OF TPS FOR PATCH = 300

(WITH AVERAGE THICKNESS)

```
===========================================================   -----
                                                                i
                    CRI-I  2.0          slab                  0.07074 FT    2290.3 F
                                                                i
===========================================================   -----
                    RTV-560             thin skin             0.00066 FT     546.0 F
===========================================================   -----
```

THICKNESS AND TEMPERATURE OF LAYERS FOR PATCH = 300

PANEL	LAYER01		LAYER02	
300001	0.02132	2117.38	0.00002	550.33
300002	0.02133	2114.24	0.00002	550.33
......				
......				
......				
302999	0.02117	1965.72	0.00002	550.33
303000	0.02116	1967.03	0.00002	550.33

OPTIMIZATION SYSTEM FOR TPSSYM =   400

TOTAL NUMBER OF DESIGN VARIABLES =   4

TOTAL NUMBER OF CONSTRAINS   = 1840

TOTAL NUMBER OF TEMP. CONSTRAINS =   48

TOTAL NUMBER OF TEMP. PRINTOUTS =   6

MAXIMUM TEMPERATURE OF EACH LAYER VS OUTPUT TIMES

```
    X   0.2406E+04

    1.0 B                       A
        I                       B                       B                       A
        I                                                                       B                       A
        I                                                                                               B
        I
        I
        I
        I
        I
        I
    0.0 +-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+
        I
        I
        I
        I
        I
        I
        I
        I
        I
   -1.0 +
        .00         .10         .20         .30         .40         .50         .60         .70         .80         .90      1.00
```

TIME (X 1.733E+02)

MAXIMUM TEMPERATURE OF EVERY LAYER

LAYER:	1	2
Tmax:	3000.33	8540.33
Optv:	2406.49	2299.50

VALUES OF DESIGN VARIABLES :

LAYER	DEV01	DEV02	DEV03	DEV04
1	0.00020	0.00020	0.00020	0.00020

THE ORIGINAL OBJECTIVE FUNCTION = 1771.6535645

THE RATIO OF OPTIMAL OBJECTIVE FUNCTION = 0.0020000

THE TOTAL OPTIMAL WEIGHT = 1.46587057E-03

OPTIMAL STRUCTURES OF TPS FOR PATCH = 400

(WITH AVERAGE THICKNESS)

```
============================================================   -----
                                                                 i
                  ZIRCONIA FIBERS       slab                   0.00066 FT    2406.5 F
                                                                 i
============================================================   -----
                                                                 i
                  HEAT SINK             slab                   0.65617 FT    2299.5 F
                                                                 i
============================================================   -----
```

THICKNESS AND TEMPERATURE OF LAYERS FOR PATCH = 400

PANEL	LAYER01		LAYER02	
400001	0.00020	2406.49	0.20000	2352.99
400002	0.00020	2391.05	0.20000	2337.80

```
..................................................................
..................................................................
..................................................................
  400899    0.00020    1759.96    0.20000    1710.11

  400900    0.00020    1747.60    0.20000    1697.63
```

OPTIMIZATION SYSTEM FOR TPSSYM = 500

```
TOTAL NUMBER OF DESIGN VARIABLES =     6

TOTAL NUMBER OF CONSTRAINS       =   600

TOTAL NUMBER OF TEMP. CONSTRAINS =    72

TOTAL NUMBER OF TEMP. PRINTOUTS  =     6

WARNING: MODIFICATION EXEEDS ALLOWED VALUE
```

MAXIMUM TEMPERATURE OF EACH LAYER VS OUTPUT TIMES

```
   X   0.2670E+04
1.0 A                       A
    |                                               A                       A
    |                                                                                               A
    |
    |
    |
    |
    |
    B
    |                       B                       B
0.0 +-----------+-----------+-----------+-----------+-----------+-----------B-----------+-----------B-----------+-----------+
    |
    |
    |
    |
```

```
      |
      |
      |
      |
      |
-1.0 +
      .00      .10      .20      .30      .40      .50      .60      .70      .80      .90     1.00

                                              TIME  ( X 1.733E+02 )
```

MAXIMUM TEMPERATURE OF EVERY LAYER

LAYER:	1	2
Tmax:	3000.33	550.33
Optv:	2670.36	547.98

VALUES OF DESIGN VARIABLES :

LAYER	DEV01	DEV02	DEV03	DEV04	DEV05	DEV06
1	0.03480	0.04058	0.03493	0.04081	0.03503	0.04102

THE ORIGINAL OBJECTIVE FUNCTION = 531.4960938

THE RATIO OF OPTIMAL OBJECTIVE FUNCTION = 0.3848726

THE TOTAL OPTIMAL WEIGHT = 7.15747357E-01

OPTIMAL STRUCTURES OF TPS FOR PATCH = 500

(WITH AVERAGE THICKNESS)

```
============================================================  -----
                                                                i
                  ZIRCONIA FIBERS      slab                 0.12422 FT   2670.4 F
                                                                i
============================================================  -----
                  RTV-560              thin skin            0.00066 FT    548.0 F
============================================================  -----
```

```
        THICKNESS AND TEMPERATURE OF LAYERS FOR PATCH =      500


  PANEL   LAYER01             LAYER02

 500001   0.03480   2106.05   0.00002    550.33

 500002   0.03502   2127.22   0.00002    550.33

...................................................................

...................................................................

...................................................................

 500269   0.04091   2660.05   0.00002    550.33

 500270   0.04102   2670.36   0.00002    550.33



                   OPTIMIZATION SYSTEM FOR TPSSYM =   700



 TOTAL NUMBER OF DESIGN VARIABLES =    6

 TOTAL NUMBER OF CONSTRAINS       = 1060

 TOTAL NUMBER OF TEMP. CONSTRAINS =   72

 TOTAL NUMBER OF TEMP. PRINTOUTS  =    6

 WARNING: MODIFICATION EXEEDS ALLOWED VALUE



MAXIMUM TEMPERATURE OF EACH LAYER VS OUTPUT TIMES

    X    0.2128E+04

   1.0 A                      A

       |                        A                        A                        A

       |

       |

       |

       |

       |

       B

       |                        B

       |                        B                        B
```

```
 0.0 +-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------B-----------+-----------+
     |
     |
     |
     |
     |
     |
     |
     |
     |
-1.0 +
     .00        .10         .20         .30         .40         .50         .60         .70         .80         .90        1.00
                                                         TIME  ( X 1.733E+02 )
```

MAXIMUM TEMPERATURE OF EVERY LAYER

LAYER:	1	2
Tmax:	2400.33	550.33
Optv:	2128.29	540.76

VALUES OF DESIGN VARIABLES :

LAYER	DEV01	DEV02	DEV03	DEV04	DEV05	DEV06
1	0.02128	0.01810	0.02071	0.01728	0.02063	0.01725

THE ORIGINAL OBJECTIVE FUNCTION = 1742.1259766

THE RATIO OF OPTIMAL OBJECTIVE FUNCTION = 0.1914894

THE TOTAL OPTIMAL WEIGHT = 2.09356866E+00

OPTIMAL STRUCTURES OF TPS FOR PATCH = 700

(WITH AVERAGE THICKNESS)

```
=============================================================   -----
                                                                  i
                  CRI-I  2.0          slab                 0.06302 FT   2128.3 F
                                                                  i
```

```
=========================================================  -----
                    RTV-560           thin skin          0.00066 FT    540.8 F
=========================================================  -----


        THICKNESS AND TEMPERATURE OF LAYERS FOR PATCH =     700


  PANEL   LAYER01             LAYER02

 700001   0.02128   2128.29   0.00002    550.33

 700002   0.02124   2123.60   0.00002    550.33

...............................................................

...............................................................

...............................................................

 700499   0.01728   1655.68   0.00002    550.33

 700500   0.01725   1651.83   0.00002    550.33



                  OPTIMIZATION SYSTEM FOR TPSSYM =  1200



 TOTAL NUMBER OF DESIGN VARIABLES =    9

 TOTAL NUMBER OF CONSTRAINS       = 6162

 TOTAL NUMBER OF TEMP. CONSTRAINS =  180

 TOTAL NUMBER OF TEMP. PRINTOUTS  =    6


MAXIMUM TEMPERATURE OF EACH LAYER VS OUTPUT TIMES

    X   0.2743E+04

   1.0 B                    A
       |                    B                    A
       |                                         B                    B                    A
       |                                                                                   B
       |
       |
       |
```

```
      |
      |
      |
 0.0 +-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+
      |
      |
      |
      |
      |
      |
      |
      |
      |
-1.0 +
     .00        .10        .20        .30        .40        .50        .60        .70        .80        .90       1.00

                                                    TIME   ( X 1.733E+02 )
```

MAXIMUM TEMPERATURE OF EVERY LAYER

LAYER:	1	2
Tmax:	3000.33	8540.33
Optv:	2743.16	2613.32

VALUES OF DESIGN VARIABLES :

LAYER	DEV01	DEV02	DEV03	DEV04	DEV05	DEV06	DEV07	DEV08	DEV09
1	0.00020	0.00020	0.00020	0.00020	0.00020	0.00020	0.00020	0.00020	0.00020

THE ORIGINAL OBJECTIVE FUNCTION = 5905.4257812

THE RATIO OF OPTIMAL OBJECTIVE FUNCTION = 0.0020000

THE TOTAL OPTIMAL WEIGHT = 1.85629520E-02

OPTIMAL STRUCTURES OF TPS FOR PATCH = 1200

(WITH AVERAGE THICKNESS)

== -----

```
                                                        i

                ZIRCONIA FIBERS     slab                0.00066 FT   2743.2 F

                                                        i

=============================================================  -----

                                                        i

                HEAT SINK           slab                0.65617 FT   2613.3 F

                                                        i

=============================================================  -----


        THICKNESS AND TEMPERATURE OF LAYERS FOR PATCH =     1200


  PANEL   LAYER01              LAYER02

1200001   0.00020   2008.14   0.20000   1962.09

1200002   0.00020   1997.29   0.20000   1951.04

.................................................................

.................................................................

.................................................................

1202999   0.00020    691.81   0.20000    642.59

1203000   0.00020    677.43   0.20000    628.26



 T O T A L   M A S S   O F   B O T H   S I D E S :  0.15660E+02 (KG  ),  C. G.  F R O M   X=0.   I S :  0.21950E+01 (M   )



                                        ****************************************
                                        ***                                  ***
                                        *** T P S O P T   T E R M I N A T E D ***
                                        ***                                  ***
                                        ***          N O R M A L L Y         ***
                                        ***                                  ***
                                        ***     18:25:40     08/17/2009      ***
                                        ***                                  ***
                                        ****************************************
```

Listing 8.6.3 Output of Mass change due to TPS: mass_tps.dat

```
15.65999    34.37291
```

8.7 Run SMB for Structural Design

Input Files:

File Name	Type	Remarks	See Listing
smb_run.inp	Standard input file	Required	Shown in listing 8.7.1
trajct.dat	Trajectory data generated by UPTOP	Inserted into the Standard input file smb_run.inp by the **INCLUDE** bulk data card	Shown in Listing 8.4.3
geom_data.dat	Aerodynamic mesh generated by UCDA	Imported by the ASSIGN AEROBASE executive control command	Not Shown

Output Files:

File Name	Type	Remarks	See Listing
smb_run.out	Standard output file	Print out results	Shown in Listing 8.7.2
RDOF_EIGEN.FREE	Eigenvalues and Eigenvectors of the beam model	Input file for TRIM and ASE analysis	Shown in Listing 8.7.3
masschng.dat	Mass of the structural skin designed by SMB	Input file for UCDA to update the change of weight due to structure	Shown in Listing 8.7.4

8.7.1 Descriptions of the Input File: SMB_RUN.INP (Shown in Listing 8.7.1)

The aerodynamic mesh of the SEM configuration generated by UCDA is stored in the file "geom_data.dat" and imported into the SMB module by the executive control command shown as follows:

ASSIGN AEROBASE=geom_data.dat

Based on this aerodynamic mesh, SMB computes the width and height at 20 axial stations to approximate the cross section of the SEM configuration as rectangular boxes. Then, the SMB module constructs a beam finite element model with 20 grid points and 19 beam elements along the x axis of the vehicle. The area moment of inertias of each beam element is calculated based on the size of the rectangular box at each axial station with the optimum skin thickness that is to be designed by the fully stressed design method. Meanwhile, the vehicle weight calculated by UCDA and stored in the file "geom_data.dat" is distributed at each grid points of the beam model to represent the non-structural weight of the SEM configuration.

There is only one subcase defined by the case control command shown as follows:

BEAM=100

This case control command refers to a **BEAMFSD** bulk data card with ID = 100 in the bulk data section. In this **BEAMFSD** bulk data card, the material properties of the Aluminum along with a failure stress = $1.5\text{x}10^6$ is specified. It also defines an initial and minimum skin thickness as 0.00001and 0.000001, respectively, as well as a load factor of 1.5. The minimum skin thickness serves as a lower bound of thickness used by the Fully Stressed Design method. The load factor is used as a multiplication factor to the computed aerodynamic loads along on the trajectory. It should be noted that since the units of length and mass defined by UCDA for the SEM

configuration are in Meter and KG, respectively, the units of length and mass involved in the BEAMFSD input entries must be consistent with that of UCDA.

The trajectory is computed by UPTOP which is stored on the file "trajct.dat" that consists of one **TRAJCT** bulk data card with ID = 100 and one TIMESP bulk data card. The TRAJCT bulk data card is referred to by the **TRJLST** bulk data card with ID = 1. The TIMESP bulk data card is used only by the TPSOPT module and is not used by the SMB module. This trajectory file "trajct.dat" is automatically inserted into the bulk data section by the INCLUDE bulk data card shown as follows:

```
INCLUDE    trajct.dat
```

8.7.2 Descriptions of the Standard Output File: smb_run.lut (Shown in Listing 8.7.2)

The standard output file first prints out the input bulk data cards in an alphabetic order. Then it shows the 20 grid point locations and the non-structural masses at each grid points. The total non-structural mass is 572.7 KG that serves as the initial mass distribution of the beam model. The stiffness of the 19 beam elements with the initial skin thickness (0.00001) in term of EI and GJ is printed next.

After the Fully Stressed design computation is completed, SMB prints out the optimum thickness and the mass distribution of the beam model. This optimum thickness along with the initial thickness of the 19 beam element is shown in Figure 8.7.1.. The total mass of the optimized structural model is 610.0 KG which shows a 37.3 KG increase of mass due to the structural skin.

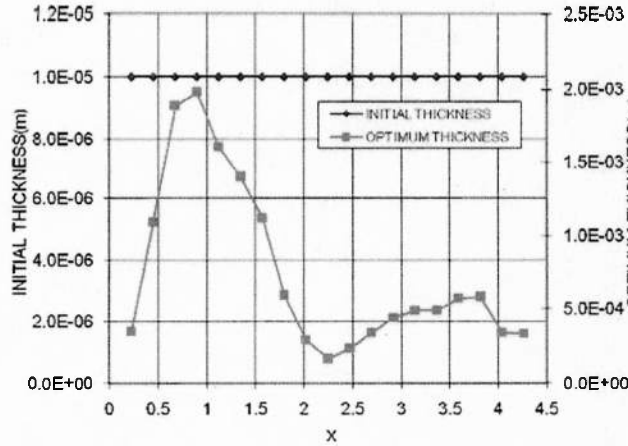


Figure 8.7.1 Optimum Thickness of the SEM configuration

Next, the EI and GJ distribution followed by the natural frequencies of the optimized beam model are printed out. These EI and GJ distributions are depicted in Figure 8.7.2 and the natural frequencies of the first 5 elastic modes are shown in Table 8.7.2.

Finally, an NASTRAN input file of the optimized beam model is printed in the standard file that allows the user to use NASTRAN to verify the SMB solution.

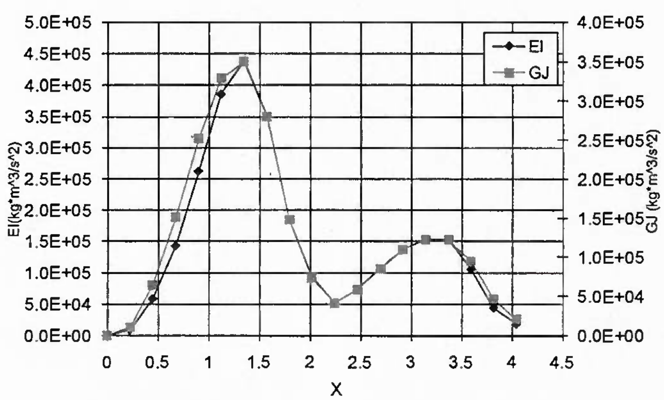


Figure 8.7.2 EI and GJ of the Optimized Beam Model for the SEM Configuration

Table 8.7.2 Natural Frequencies of the First Elastic Modes

BENDING MODE NO.	NATURAL FREQUENCY(Hz)
1	6.30E+00
2	2.04E+01
3	3.53E+01
4	5.16E+01
5	7.22E+01

8.7.3 Other Output Files: RDOF_EIGEN.FREE (Shown in Listing 8.7.3) and masschng.dat (Shown in Listing 8.7.4)

The file "RDOF_EIGEN.FREE" contains the natural frequencies and generalized masses of the first 20 modes. Note that the first 3 modes are corresponding to the fore-aft, plunge, and pitch rigid body modes. The first 3 elastic modes of the optimized beam model are depicted in Figure 8.7.3

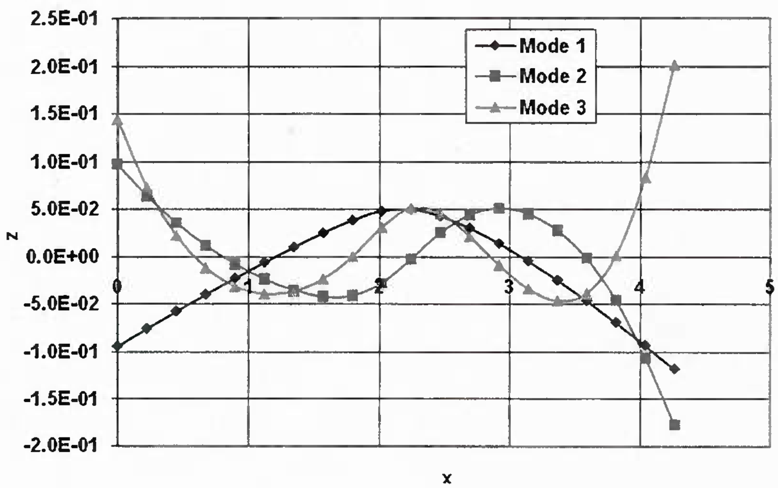


Figure 8.7.3 The First 3 Elastic Modes of the Optimized Beam Model

The file "masschng.dat" contains the locations of the 20 grid points and the incremental masses due to the structural skin at those 20 grid points. This file will be imported back to UCDA for

the next design cycle to include the impact of the structural skin weight on the weight and center of gravity of the whole vehicle.

Listing 8.7.1 Standard Input File: smb_run.inp

```
assign aerobase=geom_data.dat,print=1
cend
title= SEM Beam Model
echo=sort
subcase =1
   Beam=100
begin bulk
$
include 'trajct.dat'
$
beamfsd 100     1       6.895E092.592E09 .33     .00001 1.50    1.5E6
        .5      .01     .000001 6750.   .0001
trjlst  1
        100
enddata
```

Listing 8.7.2 Standard Output File: smb_run.out

```
                    E X E C U T I V E   C O N T R O L   S U M M A R Y


|...1...|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|..10...|


assign aerobase=geom_data.dat,print=1

cend


                         C A S E   C O N T R O L   S U M M A R Y


                 S I N G L E   P R E C I S I O N   C O M P U T A T I O N


        M A X I M U M   A L L O C A B L E   M E M O R Y  = 800  M E G A B Y T E S


|...1...|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|..10...|
```

```
title= SEM Beam Model

echo=sort

subcase =1

Beam=100

begin bulk
```

```
                    S O R T E D   B U L K   D A T A   E C H O

CARD
COUNT        |...1...|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|..10...|


    1 -      BEAMFSD 100     1       6.895E092.592E09.33     .00001  1.50    1.5E6
    2 -              .5      .01     .000001 6750.   .0001
    3 -      TIMESP  201     0.000   45.000  90.000  135.000 180.000 208.000
    4 -      TRAJCT  100     10
    5 -              9.0     6.1200  22332.  1.250
    6 -              18.0    6.2500  22375.  1.260
    7 -              27.0    6.3800  22482.  1.260
    8 -              36.0    6.4900  22645.  1.270
    9 -              45.0    6.5800  22841.  1.270
   10 -              54.0    6.6600  23063.  1.280
   11 -              63.0    6.7300  23301.  1.280
   12 -              72.0    6.7900  23547.  1.280
   13 -              81.0    6.8500  23785.  1.290
   14 -              90.0    6.9000  24003.  1.290
   15 -              99.0    6.9500  24186.  1.300
   16 -              108.0   6.9900  24325.  1.300
   17 -              117.0   7.0300  24412.  1.310
   18 -              126.0   7.0700  24451.  1.310
   19 -              135.0   7.1200  24454.  1.310
   20 -              144.0   7.1900  24439.  1.320
   21 -              153.0   7.2600  24431.  1.320
   22 -              162.0   7.3500  24457.  1.330
   23 -              171.0   7.4500  24549.  1.330
   24 -              180.0   7.5600  24732.  1.340
```

```
                189.0   7.6900  25031.  1.340

                198.0   7.8300  25460.  1.340

                207.0   7.9800  26019.  1.350

                208.0   8.0000  26089.  1.350          TECPLOT          1209.PLT

          TRJLST  1

                100

          ENDDATA
```

```
***************************************
*                                     *
*       SUBCASE        =        1     *
*       DISCIPLINE     = BEAM         *
*       BULK ENTRY ID =       100     *
*                                     *
***************************************
```

F I N I T E   E L E M E M T   M O D E L   D E S C R I P T I O N

GRID ID	COORDINATE			CONCENTATED
	X	Y	Z	MASS
1	0.000	0.000	0.000	4.639
2	0.225	0.000	0.000	14.949
3	0.449	0.000	0.000	17.948
4	0.674	0.000	0.000	22.341
5	0.898	0.000	0.000	29.908
6	1.123	0.000	0.000	37.558
7	1.348	0.000	0.000	38.891
8	1.572	0.000	0.000	38.889
9	1.797	0.000	0.000	38.889

10	2.021	0.000	0.000	38.896
11	2.246	0.000	0.000	38.904
12	2.470	0.000	0.000	38.913
13	2.695	0.000	0.000	38.926
14	2.920	0.000	0.000	38.918
15	3.144	0.000	0.000	38.870
16	3.369	0.000	0.000	36.775
17	3.593	0.000	0.000	23.666
18	3.818	0.000	0.000	18.136
19	4.043	0.000	0.000	14.431
20	4.267	0.000	0.000	2.224

*TOTAL MASS = 0.57267133E+03

ELEMENT	CROSS SECTION(BOX)			MOMENT OF INERTIA			STIFFNESS	
ID	WIDTH	HEIGHT	THICKNESS	Izz	Iyy	J	BENDING(EI)	TORSION(GJ)
1	0.57E+0	0.11E+0	0.10E-4	0.48E-6	0.36E-7	0.11E-6	0.25038E+03	0.29666E+03
2	0.60E+0	0.15E+0	0.10E-4	0.65E-6	0.77E-7	0.23E-6	0.53007E+03	0.58614E+03
3	0.61E+0	0.18E+0	0.10E-4	0.71E-6	0.11E-6	0.30E-6	0.74271E+03	0.78581E+03
4	0.61E+0	0.23E+0	0.10E-4	0.81E-6	0.19E-6	0.48E-6	0.13039E+04	0.12551E+04
5	0.61E+0	0.31E+0	0.10E-4	0.95E-6	0.34E-6	0.78E-6	0.23698E+04	0.20184E+04
6	0.61E+0	0.35E+0	0.10E-4	0.10E-5	0.45E-6	0.96E-6	0.31047E+04	0.24820E+04
7	0.61E+0	0.35E+0	0.10E-4	0.10E-5	0.45E-6	0.96E-6	0.31272E+04	0.24956E+04
8	0.61E+0	0.35E+0	0.10E-4	0.10E-5	0.45E-6	0.96E-6	0.31229E+04	0.24930E+04
9	0.61E+0	0.35E+0	0.10E-4	0.10E-5	0.45E-6	0.96E-6	0.31242E+04	0.24938E+04
10	0.61E+0	0.35E+0	0.10E-4	0.10E-5	0.45E-6	0.96E-6	0.31255E+04	0.24946E+04
11	0.61E+0	0.35E+0	0.10E-4	0.10E-5	0.45E-6	0.96E-6	0.31268E+04	0.24954E+04
12	0.61E+0	0.35E+0	0.10E-4	0.10E-5	0.45E-6	0.96E-6	0.31290E+04	0.24967E+04
13	0.61E+0	0.35E+0	0.10E-4	0.10E-5	0.45E-6	0.96E-6	0.31303E+04	0.24974E+04
14	0.61E+0	0.35E+0	0.10E-4	0.10E-5	0.45E-6	0.96E-6	0.31243E+04	0.24938E+04
15	0.61E+0	0.35E+0	0.10E-4	0.10E-5	0.45E-6	0.96E-6	0.31196E+04	0.24910E+04
16	0.61E+0	0.28E+0	0.10E-4	0.89E-6	0.27E-6	0.64E-6	0.18531E+04	0.16646E+04
17	0.61E+0	0.18E+0	0.10E-4	0.71E-6	0.11E-6	0.31E-6	0.75761E+03	0.79915E+03
18	0.61E+0	0.15E+0	0.10E-4	0.66E-6	0.79E-7	0.23E-6	0.54205E+03	0.59991E+03
19	0.33E+0	0.11E+0	0.10E-4	0.12E-6	0.20E-7	0.55E-7	0.13884E+03	0.14278E+03

F U L L Y   S T R E S S E D   D E S I G N   R E S U L T

DESIGN VARIABLE   :   THICKNESS OF CROSS SECTION(BOX)

MINIMUM THICKNESS :   0.1000000E-03

ELEMENTS ID	INITIAL THICKNESS	OPTIMUM THICKNESS	INCREMENTS
1	0.99999997E-05	0.35148129E-03	0.34148130E-03
2	0.99999997E-05	0.10882088E-02	0.10782088E-02
3	0.99999997E-05	0.18891594E-02	0.18791595E-02
4	0.99999997E-05	0.19792626E-02	0.19692625E-02
5	0.99999997E-05	0.16131498E-02	0.16031498E-02
6	0.99999997E-05	0.13999925E-02	0.13899925E-02
7	0.99999997E-05	0.11146659E-02	0.11046659E-02
8	0.99999997E-05	0.59418526E-03	0.58418524E-03
9	0.99999997E-05	0.29307799E-03	0.28307800E-03
10	0.99999997E-05	0.16511255E-03	0.15511255E-03
11	0.99999997E-05	0.23398212E-03	0.22398212E-03
12	0.99999997E-05	0.33900252E-03	0.32900253E-03
13	0.99999997E-05	0.44028691E-03	0.43028692E-03
14	0.99999997E-05	0.48912334E-03	0.47912335E-03
15	0.99999997E-05	0.48940675E-03	0.47940676E-03
16	0.99999997E-05	0.56959159E-03	0.55959157E-03
17	0.99999997E-05	0.58346102E-03	0.57346100E-03
18	0.99999997E-05	0.34013751E-03	0.33013753E-03
19	0.99999997E-05	0.33359733E-03	0.32359734E-03

GRID ID	COORDINATE			CONCENTATED
	X	Y	Z	MASS
1	0.000	0.000	0.000	4.990
2	0.225	0.000	0.000	16.541
3	0.449	0.000	0.000	21.447
4	0.674	0.000	0.000	27.131
5	0.898	0.000	0.000	34.684
6	1.123	0.000	0.000	41.834

7	1.348	0.000	0.000	42.539
8	1.572	0.000	0.000	41.359
9	1.797	0.000	0.000	40.156
10	2.021	0.000	0.000	39.536
11	2.246	0.000	0.000	39.457
12	2.470	0.000	0.000	39.720
13	2.695	0.000	0.000	40.035
14	2.920	0.000	0.000	40.247
15	3.144	0.000	0.000	40.270
16	3.369	0.000	0.000	38.228
17	3.593	0.000	0.000	25.107
18	3.818	0.000	0.000	19.207
19	4.043	0.000	0.000	15.026
20	4.267	0.000	0.000	2.437

*TOTAL MASS = 0.60995239E+03

ELEMENT	CROSS SECTION(BOX)			MOMENT OF INERTIA			STIFFNESS	
ID	WIDTH	HEIGHT	THICKNESS	Izz	Iyy	J	BENDING(EI)	TORSION(GJ)
1	0.57E+0	0.11E+0	0.35E-3	0.17E-4	0.13E-5	0.40E-5	0.88621E+04	0.10494E+05
2	0.60E+0	0.15E+0	0.11E-2	0.71E-4	0.85E-5	0.25E-4	0.58627E+05	0.64732E+05
3	0.61E+0	0.18E+0	0.19E-2	0.14E-3	0.21E-4	0.59E-4	0.14381E+06	0.15179E+06
4	0.61E+0	0.23E+0	0.20E-2	0.16E-3	0.38E-4	0.98E-4	0.26345E+06	0.25306E+06
5	0.61E+0	0.31E+0	0.16E-2	0.16E-3	0.56E-4	0.13E-3	0.38741E+06	0.32955E+06
6	0.61E+0	0.35E+0	0.14E-2	0.15E-3	0.64E-4	0.14E-3	0.43922E+06	0.35081E+06
7	0.61E+0	0.35E+0	0.11E-2	0.12E-3	0.51E-4	0.11E-3	0.35147E+06	0.28029E+06
8	0.61E+0	0.35E+0	0.59E-3	0.62E-4	0.27E-4	0.57E-4	0.18637E+06	0.14873E+06
9	0.61E+0	0.35E+0	0.29E-3	0.30E-4	0.13E-4	0.28E-4	0.91759E+05	0.73230E+05
10	0.61E+0	0.35E+0	0.17E-3	0.17E-4	0.75E-5	0.16E-4	0.51666E+05	0.41232E+05
11	0.61E+0	0.35E+0	0.23E-3	0.24E-4	0.11E-4	0.23E-4	0.73285E+05	0.58477E+05
12	0.61E+0	0.35E+0	0.34E-3	0.35E-4	0.15E-4	0.33E-4	0.10634E+06	0.84829E+05
13	0.61E+0	0.35E+0	0.44E-3	0.46E-4	0.20E-4	0.43E-4	0.13827E+06	0.11028E+06
14	0.61E+0	0.35E+0	0.49E-3	0.51E-4	0.22E-4	0.47E-4	0.15337E+06	0.12238E+06
15	0.61E+0	0.35E+0	0.49E-3	0.51E-4	0.22E-4	0.47E-4	0.15323E+06	0.12231E+06
16	0.61E+0	0.28E+0	0.57E-3	0.51E-4	0.15E-4	0.37E-4	0.10609E+06	0.95252E+05
17	0.61E+0	0.18E+0	0.58E-3	0.42E-4	0.65E-5	0.18E-4	0.44535E+05	0.46943E+05
18	0.61E+0	0.15E+0	0.34E-3	0.23E-4	0.27E-5	0.79E-5	0.18528E+05	0.20497E+05

19	0.33E+0	0.11E+0	0.33E-3	0.39E-5	0.68E-6	0.18E-5	0.46657E+04	0.47946E+04

M A X I M U M   S T R E S S   A F T E R   F U L L Y   S T R E S S E D   D E S I G N

LOAD CASE NUMBER	ELEMENT ID	STRESS
1	10	0.30549E+07
2	2	0.27570E+07
3	2	0.27413E+07
4	2	0.29748E+07
5	2	0.27805E+07

R E A L   E I G E N V A L U E S   O F   O P T I M U M   S Y S T E M

MODE NO.	EXTRACTION ORDER	EIGENVALUE	RADIANS	CYCLES	GENERALIZED MASS	GENERALIZED STIFFNESS
1	1	0.328012E-02	0.572723E-01	0.911518E-02	0.100000E+01	0.328012E-02
2	2	0.763687E-01	0.276349E+00	0.439823E-01	0.100000E+01	0.763687E-01
3	3	0.362413E+00	0.602008E+00	0.958125E-01	0.100000E+01	0.362413E+00
4	4	0.156646E+04	0.395785E+02	0.629912E+01	0.100000E+01	0.156646E+04
5	5	0.164186E+05	0.128135E+03	0.203934E+02	0.100000E+01	0.164186E+05
6	6	0.211866E+05	0.145556E+03	0.231660E+02	0.100000E+01	0.211866E+05
7	7	0.490913E+05	0.221566E+03	0.352633E+02	0.100000E+01	0.490913E+05
8	8	0.105222E+06	0.324380E+03	0.516267E+02	0.100000E+01	0.105222E+06
9	9	0.136950E+06	0.370068E+03	0.588981E+02	0.100000E+01	0.136950E+06
10	10	0.206066E+06	0.453945E+03	0.722476E+02	0.100000E+01	0.206066E+06
11	11	0.284621E+06	0.533499E+03	0.849090E+02	0.100000E+01	0.284621E+06
12	12	0.354590E+06	0.595475E+03	0.947727E+02	0.100000E+01	0.354590E+06
13	13	0.443067E+06	0.665633E+03	0.105939E+03	0.100000E+01	0.443067E+06
14	14	0.547201E+06	0.739730E+03	0.117732E+03	0.100000E+01	0.547201E+06
15	15	0.653282E+06	0.808259E+03	0.128638E+03	0.100000E+01	0.653282E+06
16	16	0.817484E+06	0.904148E+03	0.143900E+03	0.100000E+01	0.817484E+06
17	17	0.824236E+06	0.907875E+03	0.144493E+03	0.100000E+01	0.824236E+06
18	18	0.107971E+07	0.103909E+04	0.165376E+03	0.100000E+01	0.107971E+07
19	19	0.121719E+07	0.110326E+04	0.175590E+03	0.100000E+01	0.121719E+07

20	20	0.135788E+07	0.116528E+04	0.185460E+03	0.100000E+01	0.135788E+07
21	21	0.152273E+07	0.123399E+04	0.196396E+03	0.100000E+01	0.152273E+07
22	22	0.176706E+07	0.132931E+04	0.211566E+03	0.100000E+01	0.176706E+07
23	23	0.204883E+07	0.143137E+04	0.227810E+03	0.100000E+01	0.204883E+07
24	24	0.210969E+07	0.145248E+04	0.231169E+03	0.100000E+01	0.210969E+07
25	25	0.256708E+07	0.160221E+04	0.255000E+03	0.100000E+01	0.256708E+07
26	26	0.257644E+07	0.160513E+04	0.255464E+03	0.100000E+01	0.257644E+07
27	27	0.319019E+07	0.178611E+04	0.284268E+03	0.100000E+01	0.319019E+07
28	28	0.369745E+07	0.192288E+04	0.306035E+03	0.100000E+01	0.369745E+07
29	29	0.386050E+07	0.196482E+04	0.312710E+03	0.100000E+01	0.386050E+07
30	30	0.446682E+07	0.211349E+04	0.336372E+03	0.100000E+01	0.446682E+07
31	31	0.458788E+07	0.214193E+04	0.340899E+03	0.100000E+01	0.458788E+07
32	32	0.492742E+07	0.221978E+04	0.353289E+03	0.100000E+01	0.492742E+07
33	33	0.596267E+07	0.244186E+04	0.388634E+03	0.100000E+01	0.596267E+07
34	34	0.685215E+07	0.261766E+04	0.416614E+03	0.100000E+01	0.685215E+07
35	35	0.804543E+07	0.283645E+04	0.451435E+03	0.100000E+01	0.804543E+07
36	36	0.839791E+07	0.289791E+04	0.461217E+03	0.100000E+01	0.839791E+07
37	37	0.116353E+08	0.341106E+04	0.542886E+03	0.100000E+01	0.116353E+08
38	38	0.122275E+08	0.349678E+04	0.556530E+03	0.100000E+01	0.122275E+08
39	39	0.153337E+08	0.391582E+04	0.623223E+03	0.100000E+01	0.153337E+08
40	40	0.286732E+08	0.535474E+04	0.852233E+03	0.100000E+01	0.286732E+08
41	41	0.210351E+11	0.145035E+06	0.230830E+05	0.100000E+01	0.210351E+11
42	42	0.295906E+11	0.172019E+06	0.273777E+05	0.100000E+01	0.295906E+11
43	43	0.371050E+11	0.192626E+06	0.306575E+05	0.100000E+01	0.371050E+11
44	44	0.401755E+11	0.200438E+06	0.319008E+05	0.100000E+01	0.401755E+11
45	45	0.530688E+11	0.230367E+06	0.366640E+05	0.100000E+01	0.530688E+11
46	46	0.587319E+11	0.242347E+06	0.385707E+05	0.100000E+01	0.587319E+11
47	47	0.659566E+11	0.256820E+06	0.408742E+05	0.100000E+01	0.659566E+11
48	48	0.691115E+11	0.262891E+06	0.418404E+05	0.100000E+01	0.691115E+11
49	49	0.786366E+11	0.280422E+06	0.446306E+05	0.100000E+01	0.786366E+11
50	50	0.983478E+11	0.313604E+06	0.499117E+05	0.100000E+01	0.983478E+11
51	51	0.113244E+12	0.336517E+06	0.535584E+05	0.100000E+01	0.113244E+12
52	52	0.122690E+12	0.350272E+06	0.557475E+05	0.100000E+01	0.122690E+12
53	53	0.144016E+12	0.379494E+06	0.603983E+05	0.100000E+01	0.144016E+12
54	54	0.150538E+12	0.387992E+06	0.617508E+05	0.100000E+01	0.150538E+12
55	55	0.182569E+12	0.427280E+06	0.680038E+05	0.100000E+01	0.182569E+12

56	56	0.185401E+12	0.430582E+06	0.685293E+05	0.100000E+01	0.185401E+12
57	57	0.226531E+12	0.475953E+06	0.757503E+05	0.100000E+01	0.226531E+12
58	58	0.292183E+12	0.540539E+06	0.860295E+05	0.100000E+01	0.292183E+12
59	59	0.381235E+12	0.617442E+06	0.982690E+05	0.100000E+01	0.381235E+12
60	60	0.484582E+12	0.696119E+06	0.110791E+06	0.100000E+01	0.484582E+12

N A S T R A N   I N P U T   D E C K

```
SOL 101
CEND
SUBCASE =        1
LOAD =        1
DISP = ALL
STRESS = ALL
SUBCASE =        2
LOAD =        2
DISP = ALL
STRESS = ALL
SUBCASE =        3
LOAD =        3
DISP = ALL
STRESS = ALL
SUBCASE =        4
LOAD =        4
DISP = ALL
STRESS = ALL
SUBCASE =        5
LOAD =        5
DISP = ALL
STRESS = ALL
BEGIN BULK
PARAM, INREL, -1
PARAM, GRDPNT,1
```

```
SUPORT,1,123456
GRID          1         0.000   0.000   0.000
GRID          2         0.225   0.000   0.000
GRID          3         0.449   0.000   0.000
GRID          4         0.674   0.000   0.000
GRID          5         0.898   0.000   0.000
GRID          6         1.123   0.000   0.000
GRID          7         1.348   0.000   0.000
GRID          8         1.572   0.000   0.000
GRID          9         1.797   0.000   0.000
GRID         10         2.021   0.000   0.000
GRID         11         2.246   0.000   0.000
GRID         12         2.470   0.000   0.000
GRID         13         2.695   0.000   0.000
GRID         14         2.920   0.000   0.000
GRID         15         3.144   0.000   0.000
GRID         16         3.369   0.000   0.000
GRID         17         3.593   0.000   0.000
GRID         18         3.818   0.000   0.000
GRID         19         4.043   0.000   0.000
GRID         20         4.267   0.000   0.000
CBAR          1       1       1       2   1.000   1.000   0.000
CBAR          2       2       2       3   1.000   1.000   0.000
CBAR          3       3       3       4   1.000   1.000   0.000
CBAR          4       4       4       5   1.000   1.000   0.000
CBAR          5       5       5       6   1.000   1.000   0.000
CBAR          6       6       6       7   1.000   1.000   0.000
CBAR          7       7       7       8   1.000   1.000   0.000
CBAR          8       8       8       9   1.000   1.000   0.000
CBAR          9       9       9      10   1.000   1.000   0.000
CBAR         10      10      10      11   1.000   1.000   0.000
CBAR         11      11      11      12   1.000   1.000   0.000
CBAR         12      12      12      13   1.000   1.000   0.000
CBAR         13      13      13      14   1.000   1.000   0.000
CBAR         14      14      14      15   1.000   1.000   0.000
CBAR         15      15      15      16   1.000   1.000   0.000
```

CBAR	16	16	16	17	1.000	1.000	0.000
CBAR	17	17	17	18	1.000	1.000	0.000
CBAR	18	18	18	19	1.000	1.000	0.000
CBAR	19	19	19	20	1.000	1.000	0.000
FORCE	1	1	0	0.12E+3	0.000	0.000	1.000
FORCE	1	2	0	0.30E+3	0.000	0.000	1.000
FORCE	1	3	0	-0.17E+3	0.000	0.000	1.000
FORCE	1	4	0	-0.11E+4	0.000	0.000	1.000
FORCE	1	5	0	-0.15E+4	0.000	0.000	1.000
FORCE	1	6	0	-0.21E+4	0.000	0.000	1.000
FORCE	1	7	0	-0.13E+4	0.000	0.000	1.000
FORCE	1	8	0	0.47E+3	0.000	0.000	1.000
FORCE	1	9	0	0.48E+3	0.000	0.000	1.000
FORCE	1	10	0	0.47E+3	0.000	0.000	1.000
FORCE	1	11	0	0.51E+3	0.000	0.000	1.000
FORCE	1	12	0	0.50E+3	0.000	0.000	1.000
FORCE	1	13	0	0.57E+3	0.000	0.000	1.000
FORCE	1	14	0	0.57E+3	0.000	0.000	1.000
FORCE	1	15	0	0.57E+3	0.000	0.000	1.000
FORCE	1	16	0	0.72E+3	0.000	0.000	1.000
FORCE	1	17	0	0.85E+3	0.000	0.000	1.000
FORCE	1	18	0	0.89E+3	0.000	0.000	1.000
FORCE	1	19	0	0.73E+3	0.000	0.000	1.000
FORCE	1	20	0	0.28E+3	0.000	0.000	1.000
FORCE	2	1	0	0.11E+3	0.000	0.000	1.000
FORCE	2	2	0	0.27E+3	0.000	0.000	1.000
FORCE	2	3	0	-0.16E+3	0.000	0.000	1.000
FORCE	2	4	0	-0.98E+3	0.000	0.000	1.000
FORCE	2	5	0	-0.14E+4	0.000	0.000	1.000
FORCE	2	6	0	-0.20E+4	0.000	0.000	1.000
FORCE	2	7	0	-0.12E+4	0.000	0.000	1.000
FORCE	2	8	0	0.42E+3	0.000	0.000	1.000
FORCE	2	9	0	0.43E+3	0.000	0.000	1.000
FORCE	2	10	0	0.42E+3	0.000	0.000	1.000
FORCE	2	11	0	0.46E+3	0.000	0.000	1.000
FORCE	2	12	0	0.45E+3	0.000	0.000	1.000

FORCE	2	13	0	0.51E+3	0.000	0.000	1.000
FORCE	2	14	0	0.52E+3	0.000	0.000	1.000
FORCE	2	15	0	0.51E+3	0.000	0.000	1.000
FORCE	2	16	0	0.64E+3	0.000	0.000	1.000
FORCE	2	17	0	0.76E+3	0.000	0.000	1.000
FORCE	2	18	0	0.80E+3	0.000	0.000	1.000
FORCE	2	19	0	0.65E+3	0.000	0.000	1.000
FORCE	2	20	0	0.25E+3	0.000	0.000	1.000
FORCE	3	1	0	0.11E+3	0.000	0.000	1.000
FORCE	3	2	0	0.27E+3	0.000	0.000	1.000
FORCE	3	3	0	-0.17E+3	0.000	0.000	1.000
FORCE	3	4	0	-0.98E+3	0.000	0.000	1.000
FORCE	3	5	0	-0.14E+4	0.000	0.000	1.000
FORCE	3	6	0	-0.20E+4	0.000	0.000	1.000
FORCE	3	7	0	-0.13E+4	0.000	0.000	1.000
FORCE	3	8	0	0.42E+3	0.000	0.000	1.000
FORCE	3	9	0	0.43E+3	0.000	0.000	1.000
FORCE	3	10	0	0.42E+3	0.000	0.000	1.000
FORCE	3	11	0	0.45E+3	0.000	0.000	1.000
FORCE	3	12	0	0.45E+3	0.000	0.000	1.000
FORCE	3	13	0	0.50E+3	0.000	0.000	1.000
FORCE	3	14	0	0.51E+3	0.000	0.000	1.000
FORCE	3	15	0	0.51E+3	0.000	0.000	1.000
FORCE	3	16	0	0.63E+3	0.000	0.000	1.000
FORCE	3	17	0	0.74E+3	0.000	0.000	1.000
FORCE	3	18	0	0.78E+3	0.000	0.000	1.000
FORCE	3	19	0	0.64E+3	0.000	0.000	1.000
FORCE	3	20	0	0.25E+3	0.000	0.000	1.000
FORCE	4	1	0	0.12E+3	0.000	0.000	1.000
FORCE	4	2	0	0.29E+3	0.000	0.000	1.000
FORCE	4	3	0	-0.20E+3	0.000	0.000	1.000
FORCE	4	4	0	-0.11E+4	0.000	0.000	1.000
FORCE	4	5	0	-0.15E+4	0.000	0.000	1.000
FORCE	4	6	0	-0.22E+4	0.000	0.000	1.000
FORCE	4	7	0	-0.14E+4	0.000	0.000	1.000
FORCE	4	8	0	0.44E+3	0.000	0.000	1.000

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FORCE      4     9     0 0.45E+3   0.000   0.000   1.000
FORCE      4    10     0 0.44E+3   0.000   0.000   1.000
FORCE      4    11     0 0.48E+3   0.000   0.000   1.000
FORCE      4    12     0 0.47E+3   0.000   0.000   1.000
FORCE      4    13     0 0.53E+3   0.000   0.000   1.000
FORCE      4    14     0 0.54E+3   0.000   0.000   1.000
FORCE      4    15     0 0.54E+3   0.000   0.000   1.000
FORCE      4    16     0 0.66E+3   0.000   0.000   1.000
FORCE      4    17     0 0.78E+3   0.000   0.000   1.000
FORCE      4    18     0 0.81E+3   0.000   0.000   1.000
FORCE      4    19     0 0.67E+3   0.000   0.000   1.000
FORCE      4    20     0 0.26E+3   0.000   0.000   1.000
FORCE      5     1     0 0.11E+3   0.000   0.000   1.000
FORCE      5     2     0 0.27E+3   0.000   0.000   1.000
FORCE      5     3     0-0.19E+3   0.000   0.000   1.000
FORCE      5     4     0-0.10E+4   0.000   0.000   1.000
FORCE      5     5     0-0.14E+4   0.000   0.000   1.000
FORCE      5     6     0-0.21E+4   0.000   0.000   1.000
FORCE      5     7     0-0.13E+4   0.000   0.000   1.000
FORCE      5     8     0 0.40E+3   0.000   0.000   1.000
FORCE      5     9     0 0.41E+3   0.000   0.000   1.000
FORCE      5    10     0 0.41E+3   0.000   0.000   1.000
FORCE      5    11     0 0.44E+3   0.000   0.000   1.000
FORCE      5    12     0 0.43E+3   0.000   0.000   1.000
FORCE      5    13     0 0.49E+3   0.000   0.000   1.000
FORCE      5    14     0 0.49E+3   0.000   0.000   1.000
FORCE      5    15     0 0.49E+3   0.000   0.000   1.000
FORCE      5    16     0 0.60E+3   0.000   0.000   1.000
FORCE      5    17     0 0.71E+3   0.000   0.000   1.000
FORCE      5    18     0 0.73E+3   0.000   0.000   1.000
FORCE      5    19     0 0.60E+3   0.000   0.000   1.000
FORCE      5    20     0 0.23E+3   0.000   0.000   1.000
PBAR       1          1.477E-03.171E-04.129E-05.405E-05
        -.28E+000.55E-010.28E+000.55E-010.28E+00-.55E-01-.28E+00-.55E-01
PBAR       2          1.165E-02.709E-04.850E-05.250E-04
        -.30E+000.77E-010.30E+000.77E-010.30E+00-.77E-01-.30E+00-.77E-01
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PBAR        3       1.300E-02.136E-03.209E-04.586E-04

      -.30E+000.90E-010.30E+000.90E-010.30E+00-.90E-01-.30E+00-.90E-01

PBAR        4       1.336E-02.163E-03.382E-04.976E-04

      -.30E+000.12E+000.30E+000.12E+000.30E+00-.12E+00-.30E+00-.12E+00

PBAR        5       1.298E-02.155E-03.562E-04.127E-03

      -.30E+000.16E+000.30E+000.16E+000.30E+00-.16E+00-.30E+00-.16E+00

PBAR        6       1.270E-02.146E-03.637E-04.135E-03

      -.30E+000.18E+000.30E+000.18E+000.30E+00-.18E+00-.30E+00-.18E+00

PBAR        7       1.215E-02.116E-03.510E-04.108E-03

      -.30E+000.18E+000.30E+000.18E+000.30E+00-.18E+00-.30E+00-.18E+00

PBAR        8       1.115E-02.616E-04.270E-04.574E-04

      -.30E+000.18E+000.30E+000.18E+000.30E+00-.18E+00-.30E+00-.18E+00

PBAR        9       1.565E-03.303E-04.133E-04.283E-04

      -.30E+000.18E+000.30E+000.18E+000.30E+00-.18E+00-.30E+00-.18E+00

PBAR       10       1.318E-03.171E-04.749E-05.159E-04

      -.30E+000.18E+000.30E+000.18E+000.30E+00-.18E+00-.30E+00-.18E+00

PBAR       11       1.451E-03.242E-04.106E-04.226E-04

      -.30E+000.18E+000.30E+000.18E+000.30E+00-.18E+00-.30E+00-.18E+00

PBAR       12       1.653E-03.351E-04.154E-04.327E-04

      -.30E+000.18E+000.30E+000.18E+000.30E+00-.18E+00-.30E+00-.18E+00

PBAR       13       1.849E-03.456E-04.201E-04.425E-04

      -.30E+000.18E+000.30E+000.18E+000.30E+00-.18E+00-.30E+00-.18E+00

PBAR       14       1.943E-03.507E-04.222E-04.472E-04

      -.30E+000.18E+000.30E+000.18E+000.30E+00-.18E+00-.30E+00-.18E+00

PBAR       15       1.943E-03.507E-04.222E-04.472E-04

      -.30E+000.18E+000.30E+000.18E+000.30E+00-.18E+00-.30E+00-.18E+00

PBAR       16       1.101E-02.510E-04.154E-04.367E-04

      -.30E+000.14E+000.30E+000.14E+000.30E+00-.14E+00-.30E+00-.14E+00

PBAR       17       1.924E-03.418E-04.646E-05.181E-04

      -.30E+000.91E-010.30E+000.91E-010.30E+00-.91E-01-.30E+00-.91E-01

PBAR       18       1.520E-03.226E-04.269E-05.791E-05

      -.30E+000.77E-010.30E+000.77E-010.30E+00-.77E-01-.30E+00-.77E-01

PBAR       19       1.290E-03.387E-05.677E-06.185E-05

      -.16E+000.53E-010.16E+000.53E-010.16E+00-.53E-01-.16E+00-.53E-01

CONM2      21       1           0.50E+1

      1.E-6             1.E-6                         1.E-6
```

```
CONM2       22      2       0.17E+2
        1.E-6       1.E-6               1.E-6
CONM2       23      3       0.21E+2
        1.E-6       1.E-6               1.E-6
CONM2       24      4       0.27E+2
        1.E-6       1.E-6               1.E-6
CONM2       25      5       0.35E+2
        1.E-6       1.E-6               1.E-6
CONM2       26      6       0.42E+2
        1.E-6       1.E-6               1.E-6
CONM2       27      7       0.43E+2
        1.E-6       1.E-6               1.E-6
CONM2       28      8       0.41E+2
        1.E-6       1.E-6               1.E-6
CONM2       29      9       0.40E+2
        1.E-6       1.E-6               1.E-6
CONM2       30      10      0.40E+2
        1.E-6       1.E-6               1.E-6
CONM2       31      11      0.39E+2
        1.E-6       1.E-6               1.E-6
CONM2       32      12      0.40E+2
        1.E-6       1.E-6               1.E-6
CONM2       33      13      0.40E+2
        1.E-6       1.E-6               1.E-6
CONM2       34      14      0.40E+2
        1.E-6       1.E-6               1.E-6
CONM2       35      15      0.40E+2
        1.E-6       1.E-6               1.E-6
CONM2       36      16      0.38E+2
        1.E-6       1.E-6               1.E-6
CONM2       37      17      0.25E+2
        1.E-6       1.E-6               1.E-6
CONM2       38      18      0.19E+2
        1.E-6       1.E-6               1.E-6
CONM2       39      19      0.15E+2
        1.E-6       1.E-6               1.E-6
```

```
CONM2          40       20          0.24E+1

        1.E-6           1.E-6                     1.E-6

MAT1           1 0.7E+10 0.3E+10 0.33E+0

ENDDATA
```

```
****************************************
***                                  ***
*** S   M   B     T E R M I N A T E D ***
***                                  ***
***           N O R M A L L Y        ***
***                                  ***
***       18:28:09     08/17/2009    ***
***                                  ***
****************************************
```

Listing 8.7.3 Eigenvalues and Eigenvectors of the Beam Model: RDOF_EIGEN.FREE

```
       20        20
        1       0.00000000E+00     0.00000000E+00     0.00000000E+00
        2       0.22458947E+00     0.00000000E+00     0.00000000E+00
        3       0.44917893E+00     0.00000000E+00     0.00000000E+00
        4       0.67376840E+00     0.00000000E+00     0.00000000E+00
        5       0.89835787E+00     0.00000000E+00     0.00000000E+00
        6       0.11229473E+01     0.00000000E+00     0.00000000E+00
        7       0.13475368E+01     0.00000000E+00     0.00000000E+00
        8       0.15721263E+01     0.00000000E+00     0.00000000E+00
        9       0.17967157E+01     0.00000000E+00     0.00000000E+00
       10       0.20213053E+01     0.00000000E+00     0.00000000E+00
       11       0.22458947E+01     0.00000000E+00     0.00000000E+00
       12       0.24704843E+01     0.00000000E+00     0.00000000E+00
       13       0.26950736E+01     0.00000000E+00     0.00000000E+00
       14       0.29196632E+01     0.00000000E+00     0.00000000E+00
       15       0.31442525E+01     0.00000000E+00     0.00000000E+00
       16       0.33688421E+01     0.00000000E+00     0.00000000E+00
       17       0.35934315E+01     0.00000000E+00     0.00000000E+00
       18       0.38180211E+01     0.00000000E+00     0.00000000E+00
       19       0.40426106E+01     0.00000000E+00     0.00000000E+00
       20       0.42672000E+01     0.00000000E+00     0.00000000E+00
$MODE          1
  0.57272335E-01    0.10000000E+01
        1  -0.404903816E-01   0.000000000E+00  -0.489255126E-06   0.000000000E+00  -0.380781555E-06   0.000000000E+00
        2  -0.404903815E-01   0.000000000E+00  -0.403735601E-06   0.000000000E+00  -0.380781507E-06   0.000000000E+00
        3  -0.404903807E-01   0.000000000E+00  -0.318216072E-06   0.000000000E+00  -0.380781732E-06   0.000000000E+00
        4  -0.404903819E-01   0.000000000E+00  -0.232696502E-06   0.000000000E+00  -0.380781703E-06   0.000000000E+00
        5  -0.404903830E-01   0.000000000E+00  -0.147176944E-06   0.000000000E+00  -0.380781740E-06   0.000000000E+00
        6  -0.404903877E-01   0.000000000E+00  -0.616573504E-07   0.000000000E+00  -0.380782007E-06   0.000000000E+00
        7  -0.404903890E-01   0.000000000E+00   0.238623523E-07   0.000000000E+00  -0.380782773E-06   0.000000000E+00
        8  -0.404903904E-01   0.000000000E+00   0.109382364E-06   0.000000000E+00  -0.380784766E-06   0.000000000E+00
        9  -0.404903930E-01   0.000000000E+00   0.194903123E-06   0.000000000E+00  -0.380789353E-06   0.000000000E+00
       10  -0.404903979E-01   0.000000000E+00   0.280425505E-06   0.000000000E+00  -0.380798871E-06   0.000000000E+00
       11  -0.404904020E-01   0.000000000E+00   0.365950743E-06   0.000000000E+00  -0.380815229E-06   0.000000000E+00
       12  -0.404904045E-01   0.000000000E+00   0.451479058E-06   0.000000000E+00  -0.380825553E-06   0.000000000E+00
       13  -0.404904080E-01   0.000000000E+00   0.537009134E-06   0.000000000E+00  -0.380831768E-06   0.000000000E+00
       14  -0.404904105E-01   0.000000000E+00   0.622540525E-06   0.000000000E+00  -0.380836751E-06   0.000000000E+00
       15  -0.404904097E-01   0.000000000E+00   0.708073128E-06   0.000000000E+00  -0.380844026E-06   0.000000000E+00
       16  -0.404904088E-01   0.000000000E+00   0.793608045E-06   0.000000000E+00  -0.380856754E-06   0.000000000E+00
       17  -0.404904077E-01   0.000000000E+00   0.879146456E-06   0.000000000E+00  -0.380872712E-06   0.000000000E+00
       18  -0.404904036E-01   0.000000000E+00   0.964687688E-06   0.000000000E+00  -0.380877538E-06   0.000000000E+00
       19  -0.404904012E-01   0.000000000E+00   0.105022596E-05   0.000000000E+00  -0.380854355E-06   0.000000000E+00
       20  -0.404904013E-01   0.000000000E+00   0.113575690E-05   0.000000000E+00  -0.380821590E-06   0.000000000E+00
```

```
$MODE          2
  0.27634893E+00    0.10000000E+01
      1   0.504455971E-06   0.000000000E+00  -0.365263016E-01   0.000000000E+00  -0.297418193E-01   0.000000000E+00
      2   0.504455957E-06   0.000000000E+00  -0.298466060E-01   0.000000000E+00  -0.297417714E-01   0.000000000E+00
      3   0.504455931E-06   0.000000000E+00  -0.231669195E-01   0.000000000E+00  -0.297417532E-01   0.000000000E+00
      4   0.504455930E-06   0.000000000E+00  -0.164872382E-01   0.000000000E+00  -0.297417146E-01   0.000000000E+00
      5   0.504455918E-06   0.000000000E+00  -0.980756673E-02   0.000000000E+00  -0.297416760E-01   0.000000000E+00
      6   0.504455935E-06   0.000000000E+00  -0.312790199E-02   0.000000000E+00  -0.297416534E-01   0.000000000E+00
      7   0.504455885E-06   0.000000000E+00   0.355175883E-02   0.000000000E+00  -0.297416471E-01   0.000000000E+00
      8   0.504455797E-06   0.000000000E+00   0.102314239E-01   0.000000000E+00  -0.297416901E-01   0.000000000E+00
      9   0.504455588E-06   0.000000000E+00   0.169111047E-01   0.000000000E+00  -0.297417751E-01   0.000000000E+00
     10   0.504455073E-06   0.000000000E+00   0.235908069E-01   0.000000000E+00  -0.297418451E-01   0.000000000E+00
     11   0.504453953E-06   0.000000000E+00   0.302705049E-01   0.000000000E+00  -0.297417698E-01   0.000000000E+00
     12   0.504453052E-06   0.000000000E+00   0.369501751E-01   0.000000000E+00  -0.297415578E-01   0.000000000E+00
     13   0.504452379E-06   0.000000000E+00   0.436297890E-01   0.000000000E+00  -0.297413471E-01   0.000000000E+00
     14   0.504451802E-06   0.000000000E+00   0.503093730E-01   0.000000000E+00  -0.297412592E-01   0.000000000E+00
     15   0.504451945E-06   0.000000000E+00   0.569889385E-01   0.000000000E+00  -0.297412056E-01   0.000000000E+00
     16   0.504454070E-06   0.000000000E+00   0.636685025E-01   0.000000000E+00  -0.297412410E-01   0.000000000E+00
     17   0.504454445E-06   0.000000000E+00   0.703480946E-01   0.000000000E+00  -0.297414756E-01   0.000000000E+00
     18   0.504453899E-06   0.000000000E+00   0.770277678E-01   0.000000000E+00  -0.297418286E-01   0.000000000E+00
     19   0.504453831E-06   0.000000000E+00   0.837074998E-01   0.000000000E+00  -0.297420186E-01   0.000000000E+00
     20   0.504456598E-06   0.000000000E+00   0.903872522E-01   0.000000000E+00  -0.297420940E-01   0.000000000E+00
$MODE          3
  0.60200765E+00    0.10000000E+01
      1   0.164771606E-07   0.000000000E+00  -0.841103576E-01   0.000000000E+00  -0.252457161E-01   0.000000000E+00
      2   0.164771586E-07   0.000000000E+00  -0.784404688E-01   0.000000000E+00  -0.252452761E-01   0.000000000E+00
      3   0.164771558E-07   0.000000000E+00  -0.727706762E-01   0.000000000E+00  -0.252449368E-01   0.000000000E+00
      4   0.164771535E-07   0.000000000E+00  -0.671009721E-01   0.000000000E+00  -0.252444755E-01   0.000000000E+00
      5   0.164771500E-07   0.000000000E+00  -0.614313851E-01   0.000000000E+00  -0.252439153E-01   0.000000000E+00
      6   0.164771451E-07   0.000000000E+00  -0.557619279E-01   0.000000000E+00  -0.252433584E-01   0.000000000E+00
      7   0.164771351E-07   0.000000000E+00  -0.500925957E-01   0.000000000E+00  -0.252428250E-01   0.000000000E+00
      8   0.164771187E-07   0.000000000E+00  -0.444233890E-01   0.000000000E+00  -0.252422622E-01   0.000000000E+00
      9   0.164770810E-07   0.000000000E+00  -0.387543284E-01   0.000000000E+00  -0.252415784E-01   0.000000000E+00
     10   0.164769906E-07   0.000000000E+00  -0.330854128E-01   0.000000000E+00  -0.252409723E-01   0.000000000E+00
     11   0.164768044E-07   0.000000000E+00  -0.274165823E-01   0.000000000E+00  -0.252409208E-01   0.000000000E+00
     12   0.164766558E-07   0.000000000E+00  -0.217476885E-01   0.000000000E+00  -0.252413924E-01   0.000000000E+00
     13   0.164765423E-07   0.000000000E+00  -0.160786861E-01   0.000000000E+00  -0.252418976E-01   0.000000000E+00
     14   0.164764459E-07   0.000000000E+00  -0.104095712E-01   0.000000000E+00  -0.252423144E-01   0.000000000E+00
     15   0.164762429E-07   0.000000000E+00  -0.474037818E-02   0.000000000E+00  -0.252426472E-01   0.000000000E+00
     16   0.164762467E-07   0.000000000E+00   0.928888684E-03   0.000000000E+00  -0.252429085E-01   0.000000000E+00
     17   0.164764318E-07   0.000000000E+00   0.659820563E-02   0.000000000E+00  -0.252431427E-01   0.000000000E+00
     18   0.164765001E-07   0.000000000E+00   0.122675886E-01   0.000000000E+00  -0.252434223E-01   0.000000000E+00
     19   0.164767725E-07   0.000000000E+00   0.179370280E-01   0.000000000E+00  -0.252436324E-01   0.000000000E+00
     20   0.164769397E-07   0.000000000E+00   0.236064944E-01   0.000000000E+00  -0.252437320E-01   0.000000000E+00
$MODE          4
  0.39578528E+02    0.10000000E+01
      1  -0.196674606E-10   0.000000000E+00  -0.940948699E-01   0.000000000E+00  -0.832574359E-01   0.000000000E+00
      2  -0.196569404E-10   0.000000000E+00  -0.755528337E-01   0.000000000E+00  -0.811642040E-01   0.000000000E+00
      3  -0.196438776E-10   0.000000000E+00  -0.574820026E-01   0.000000000E+00  -0.793728618E-01   0.000000000E+00
      4  -0.196294909E-10   0.000000000E+00  -0.398514493E-01   0.000000000E+00  -0.773592962E-01   0.000000000E+00
      5  -0.196085515E-10   0.000000000E+00  -0.226957854E-01   0.000000000E+00  -0.752126464E-01   0.000000000E+00
      6  -0.195733115E-10   0.000000000E+00  -0.605072729E-02   0.000000000E+00  -0.728500250E-01   0.000000000E+00
      7  -0.195189745E-10   0.000000000E+00   0.999375657E-02   0.000000000E+00  -0.698762023E-01   0.000000000E+00
      8  -0.194310574E-10   0.000000000E+00   0.251667634E-01   0.000000000E+00  -0.650673511E-01   0.000000000E+00
      9  -0.192301126E-10   0.000000000E+00   0.385939436E-01   0.000000000E+00  -0.542486112E-01   0.000000000E+00
     10  -0.187527067E-10   0.000000000E+00   0.480692442E-01   0.000000000E+00  -0.298348384E-01   0.000000000E+00
     11  -0.177861315E-10   0.000000000E+00   0.497151583E-01   0.000000000E+00   0.152179565E-01   0.000000000E+00
     12  -0.170248216E-10   0.000000000E+00   0.427938434E-01   0.000000000E+00   0.460931255E-01   0.000000000E+00
     13  -0.164465489E-10   0.000000000E+00   0.302250297E-01   0.000000000E+00   0.654000418E-01   0.000000000E+00
     14  -0.159615643E-10   0.000000000E+00   0.140827433E-01   0.000000000E+00   0.779001962E-01   0.000000000E+00
     15  -0.154475418E-10   0.000000000E+00  -0.444011542E-02   0.000000000E+00   0.865950757E-01   0.000000000E+00
     16  -0.163457478E-10   0.000000000E+00  -0.246143926E-01   0.000000000E+00   0.926210651E-01   0.000000000E+00
     17  -0.171261139E-10   0.000000000E+00  -0.460640822E-01   0.000000000E+00   0.978749675E-01   0.000000000E+00
     18  -0.172077810E-10   0.000000000E+00  -0.688371904E-01   0.000000000E+00   0.104034124E+00   0.000000000E+00
     19  -0.181612898E-10   0.000000000E+00  -0.928766367E-01   0.000000000E+00   0.108844570E+00   0.000000000E+00
     20  -0.196211395E-10   0.000000000E+00  -0.117685609E+00   0.000000000E+00   0.111273269E+00   0.000000000E+00
$MODE          5
  0.12813527E+03    0.10000000E+01
      1  -0.907625115E-11   0.000000000E+00   0.968081569E-01   0.000000000E+00   0.154702951E+00   0.000000000E+00
      2  -0.902546662E-11   0.000000000E+00   0.637533673E-01   0.000000000E+00   0.132130422E+00   0.000000000E+00
      3  -0.896248902E-11   0.000000000E+00   0.356576338E-01   0.000000000E+00   0.114445856E+00   0.000000000E+00
      4  -0.889342793E-11   0.000000000E+00   0.117573540E-01   0.000000000E+00   0.961796104E-01   0.000000000E+00
      5  -0.879336765E-11   0.000000000E+00  -0.800905964E-02   0.000000000E+00   0.784696414E-01   0.000000000E+00
      6  -0.862584956E-11   0.000000000E+00  -0.237779420E-01   0.000000000E+00   0.611194221E-01   0.000000000E+00
      7  -0.836958113E-11   0.000000000E+00  -0.354428711E-01   0.000000000E+00   0.423344610E-01   0.000000000E+00
      8  -0.795937497E-11   0.000000000E+00  -0.421502193E-01   0.000000000E+00   0.174577267E-01   0.000000000E+00
      9  -0.703515013E-11   0.000000000E+00  -0.411588404E-01   0.000000000E+00  -0.248775430E-01   0.000000000E+00
     10  -0.489271123E-11   0.000000000E+00  -0.280802414E-01   0.000000000E+00  -0.862419990E-01   0.000000000E+00
     11  -0.763923281E-12   0.000000000E+00  -0.247116908E-02   0.000000000E+00  -0.129348192E+00   0.000000000E+00
     12   0.218468815E-11   0.000000000E+00   0.250173782E-01   0.000000000E+00  -0.106471342E+00   0.000000000E+00
     13   0.414824446E-11   0.000000000E+00   0.439779910E-01   0.000000000E+00  -0.574837101E-01   0.000000000E+00
     14   0.555510239E-11   0.000000000E+00   0.509400078E-01   0.000000000E+00  -0.250947652E-02   0.000000000E+00
     15   0.731153851E-11   0.000000000E+00   0.453378353E-01   0.000000000E+00   0.523596798E-01   0.000000000E+00
     16   0.785238307E-11   0.000000000E+00   0.278018923E-01   0.000000000E+00   0.102117540E+00   0.000000000E+00
     17   0.680811381E-11   0.000000000E+00  -0.152755457E-02   0.000000000E+00   0.155252362E+00   0.000000000E+00
     18   0.606017142E-11   0.000000000E+00  -0.455361758E-01   0.000000000E+00   0.227685935E+00   0.000000000E+00
     19   0.399300425E-11   0.000000000E+00  -0.105588135E+00   0.000000000E+00   0.292053314E+00   0.000000000E+00
     20   0.400560848E-11   0.000000000E+00  -0.176909860E+00   0.000000000E+00   0.330321022E+00   0.000000000E+00
$MODE          6
  0.14555613E+03    0.10000000E+01
      1   0.451430537E-01   0.000000000E+00   0.171072781E-10   0.000000000E+00   0.297528981E-10   0.000000000E+00
      2   0.448173724E-01   0.000000000E+00   0.108209352E-10   0.000000000E+00   0.245027895E-10   0.000000000E+00
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      3   0.444136522E-01   0.000000000E+00   0.567243532E-11   0.000000000E+00   0.205285354E-10   0.000000000E+00
      4   0.439714936E-01   0.000000000E+00   0.145821895E-11   0.000000000E+00   0.165205034E-10   0.000000000E+00
      5   0.433317349E-01   0.000000000E+00  -0.184936250E-11   0.000000000E+00   0.126643738E-10   0.000000000E+00
      6   0.422625703E-01   0.000000000E+00  -0.429691255E-11   0.000000000E+00   0.899235455E-11   0.000000000E+00
      7   0.406312203E-01   0.000000000E+00  -0.588341524E-11   0.000000000E+00   0.510569235E-11   0.000000000E+00
      8   0.380291022E-01   0.000000000E+00  -0.646906729E-11   0.000000000E+00   0.194212983E-12   0.000000000E+00
      9   0.321934718E-01   0.000000000E+00  -0.560822502E-11   0.000000000E+00  -0.748326601E-11   0.000000000E+00
     10   0.187755529E-01   0.000000000E+00  -0.270906965E-11   0.000000000E+00  -0.171380536E-10   0.000000000E+00
     11  -0.665706935E-02   0.000000000E+00   0.177167264E-11   0.000000000E+00  -0.202400097E-10   0.000000000E+00
     12  -0.241979568E-01   0.000000000E+00   0.560384421E-11   0.000000000E+00  -0.122958849E-10   0.000000000E+00
     13  -0.352853940E-01   0.000000000E+00   0.720589387E-11   0.000000000E+00  -0.123345619E-11   0.000000000E+00
     14  -0.426711595E-01   0.000000000E+00   0.628238916E-11   0.000000000E+00   0.966177707E-11   0.000000000E+00
     15  -0.480636256E-01   0.000000000E+00   0.327043821E-11   0.000000000E+00   0.157369928E-10   0.000000000E+00
     16  -0.520377694E-01   0.000000000E+00  -0.211675587E-12   0.000000000E+00   0.141509428E-10   0.000000000E+00
     17  -0.543863935E-01   0.000000000E+00  -0.300581664E-11   0.000000000E+00   0.125765849E-10   0.000000000E+00
     18  -0.559362173E-01   0.000000000E+00  -0.776624123E-11   0.000000000E+00   0.337369389E-10   0.000000000E+00
     19  -0.572642995E-01   0.000000000E+00  -0.223937838E-10   0.000000000E+00   0.884017371E-10   0.000000000E+00
     20  -0.575988237E-01   0.000000000E+00  -0.512510924E-10   0.000000000E+00   0.148533026E-09   0.000000000E+00
$MODE         7
  0.22156564E+03    0.10000000E+01
      1   0.105529715E-14   0.000000000E+00   0.144094958E+00   0.000000000E+00   0.352565888E+00   0.000000000E+00
      2   0.100825832E-14   0.000000000E+00   0.724331088E-01   0.000000000E+00   0.252107231E+00   0.000000000E+00
      3   0.987348019E-15   0.000000000E+00   0.222540393E-01   0.000000000E+00   0.181248553E+00   0.000000000E+00
      4   0.978906718E-15   0.000000000E+00  -0.118119057E-01   0.000000000E+00   0.115241909E+00   0.000000000E+00
      5   0.944105450E-15   0.000000000E+00  -0.316546124E-01   0.000000000E+00   0.582112286E-01   0.000000000E+00
      6   0.867099109E-15   0.000000000E+00  -0.393952927E-01   0.000000000E+00   0.968076160E-02   0.000000000E+00
      7   0.815321115E-15   0.000000000E+00  -0.365954005E-01   0.000000000E+00  -0.339828277E-01   0.000000000E+00
      8   0.673628673E-15   0.000000000E+00  -0.236894835E-01   0.000000000E+00  -0.783292633E-01   0.000000000E+00
      9   0.390123055E-15   0.000000000E+00   0.355444777E-04   0.000000000E+00  -0.125840845E+00   0.000000000E+00
     10  -0.210060355E-15   0.000000000E+00   0.310339712E-01   0.000000000E+00  -0.135780412E+00   0.000000000E+00
     11  -0.122642120E-14   0.000000000E+00   0.513290906E-01   0.000000000E+00  -0.291346465E-01   0.000000000E+00
     12  -0.185659297E-14   0.000000000E+00   0.457303381E-01   0.000000000E+00   0.787371921E-01   0.000000000E+00
     13  -0.214504745E-14   0.000000000E+00   0.213803976E-01   0.000000000E+00   0.130876959E+00   0.000000000E+00
     14  -0.203549769E-14   0.000000000E+00  -0.882217712E-02   0.000000000E+00   0.129969208E+00   0.000000000E+00
     15  -0.222338059E-12   0.000000000E+00  -0.340284099E-01   0.000000000E+00   0.881382271E-01   0.000000000E+00
     16   0.338429084E-12   0.000000000E+00  -0.463775385E-01   0.000000000E+00   0.191597160E-01   0.000000000E+00
     17   0.185986768E-11   0.000000000E+00  -0.388748241E-01   0.000000000E+00  -0.829358340E-01   0.000000000E+00
     18   0.332671874E-11   0.000000000E+00   0.969905202E-03   0.000000000E+00  -0.255608418E+00   0.000000000E+00
     19   0.583168591E-11   0.000000000E+00   0.831077422E-01   0.000000000E+00  -0.437127873E+00   0.000000000E+00
     20   0.552204634E-11   0.000000000E+00   0.200719362E+00   0.000000000E+00  -0.566947930E+00   0.000000000E+00
$MODE         8
  0.32437990E+03    0.10000000E+01
      1  -0.274452591E-11   0.000000000E+00   0.170489903E+00   0.000000000E+00   0.600580929E+00   0.000000000E+00
      2  -0.264617816E-11   0.000000000E+00   0.546787659E-01   0.000000000E+00   0.345813255E+00   0.000000000E+00
      3  -0.252697307E-11   0.000000000E+00  -0.839010176E-02   0.000000000E+00   0.189340616E+00   0.000000000E+00
      4  -0.239919124E-11   0.000000000E+00  -0.379375658E-01   0.000000000E+00   0.640941693E-01   0.000000000E+00
      5  -0.221871777E-11   0.000000000E+00  -0.424614541E-01   0.000000000E+00  -0.256415183E-01   0.000000000E+00
      6  -0.192680862E-11   0.000000000E+00  -0.299052979E-01   0.000000000E+00  -0.840567635E-01   0.000000000E+00
      7  -0.150246680E-11   0.000000000E+00  -0.685489228E-02   0.000000000E+00  -0.116824254E+00   0.000000000E+00
      8  -0.868040358E-12   0.000000000E+00   0.207385568E-01   0.000000000E+00  -0.122684350E+00   0.000000000E+00
      9   0.431218622E-12   0.000000000E+00   0.438667933E-01   0.000000000E+00  -0.756264803E-01   0.000000000E+00
     10   0.296161078E-11   0.000000000E+00   0.452087283E-01   0.000000000E+00   0.622317833E-01   0.000000000E+00
     11   0.619203075E-11   0.000000000E+00   0.120519714E-01   0.000000000E+00   0.199866715E+00   0.000000000E+00
     12   0.661352904E-11   0.000000000E+00  -0.293139741E-01   0.000000000E+00   0.139379474E+00   0.000000000E+00
     13   0.552616883E-11   0.000000000E+00  -0.468416274E-01   0.000000000E+00   0.632153351E-02   0.000000000E+00
     14   0.379564776E-11   0.000000000E+00  -0.349804918E-01   0.000000000E+00  -0.107935727E+00   0.000000000E+00
     15   0.138401288E-11   0.000000000E+00  -0.302604868E-02   0.000000000E+00  -0.164887165E+00   0.000000000E+00
     16  -0.151928966E-11   0.000000000E+00   0.336535070E-01   0.000000000E+00  -0.149298812E+00   0.000000000E+00
     17  -0.379103660E-11   0.000000000E+00   0.569688628E-01   0.000000000E+00  -0.510727269E-01   0.000000000E+00
     18  -0.603180998E-11   0.000000000E+00   0.388398153E-01   0.000000000E+00   0.201387571E+00   0.000000000E+00
     19  -0.890446773E-11   0.000000000E+00  -0.515167512E-01   0.000000000E+00   0.540890429E+00   0.000000000E+00
     20  -0.909177014E-11   0.000000000E+00  -0.218308118E+00   0.000000000E+00   0.843532877E+00   0.000000000E+00
$MODE         9
  0.37006768E+03    0.10000000E+01
      1   0.317735637E-01   0.000000000E+00   0.221003542E-10   0.000000000E+00   0.891505283E-10   0.000000000E+00
      2   0.302918333E-01   0.000000000E+00   0.530017290E-11   0.000000000E+00   0.461424932E-10   0.000000000E+00
      3   0.285109922E-01   0.000000000E+00  -0.273169516E-11   0.000000000E+00   0.214955162E-10   0.000000000E+00
      4   0.266179926E-01   0.000000000E+00  -0.564361684E-11   0.000000000E+00   0.331849635E-11   0.000000000E+00
      5   0.239693391E-01   0.000000000E+00  -0.508231692E-11   0.000000000E+00  -0.826121762E-11   0.000000000E+00
      6   0.197394300E-01   0.000000000E+00  -0.247991394E-11   0.000000000E+00  -0.143542954E-10   0.000000000E+00
      7   0.137088399E-01   0.000000000E+00   0.100357210E-11   0.000000000E+00  -0.159236328E-10   0.000000000E+00
      8   0.493006627E-02   0.000000000E+00   0.429628035E-11   0.000000000E+00  -0.126065806E-10   0.000000000E+00
      9  -0.123543351E-01   0.000000000E+00   0.582803388E-11   0.000000000E+00  -0.600062888E-12   0.000000000E+00
     10  -0.434962968E-01   0.000000000E+00   0.341260380E-11   0.000000000E+00   0.200483262E-10   0.000000000E+00
     11  -0.746613963E-01   0.000000000E+00  -0.245406606E-11   0.000000000E+00   0.254799325E-10   0.000000000E+00
     12  -0.674934639E-01   0.000000000E+00  -0.628904900E-11   0.000000000E+00   0.545211515E-11   0.000000000E+00
     13  -0.442414719E-01   0.000000000E+00  -0.532422023E-11   0.000000000E+00  -0.135358040E-10   0.000000000E+00
     14  -0.170334578E-01   0.000000000E+00  -0.126672077E-11   0.000000000E+00  -0.203549750E-10   0.000000000E+00
     15   0.107076965E-01   0.000000000E+00   0.286784457E-11   0.000000000E+00  -0.144729598E-10   0.000000000E+00
     16   0.363999161E-01   0.000000000E+00   0.452426992E-11   0.000000000E+00   0.898729746E-12   0.000000000E+00
     17   0.542222882E-01   0.000000000E+00   0.178216409E-11   0.000000000E+00   0.212085114E-10   0.000000000E+00
     18   0.671496092E-01   0.000000000E+00  -0.496150288E-11   0.000000000E+00   0.317103159E-10   0.000000000E+00
     19   0.790560605E-01   0.000000000E+00  -0.902175209E-11   0.000000000E+00   0.386288438E-11   0.000000000E+00
     20   0.821397348E-01   0.000000000E+00  -0.109410916E-11   0.000000000E+00  -0.548792730E-10   0.000000000E+00
$MODE        10
  0.45394492E+03    0.10000000E+01
      1   0.306839988E-11   0.000000000E+00  -0.177769261E+00   0.000000000E+00  -0.889759293E+00   0.000000000E+00
      2   0.285312586E-11   0.000000000E+00  -0.168866163E-01   0.000000000E+00  -0.369516074E+00   0.000000000E+00
      3   0.259918118E-11   0.000000000E+00   0.407000026E-01   0.000000000E+00  -0.108834632E+00   0.000000000E+00
      4   0.233420688E-11   0.000000000E+00   0.476818082E-01   0.000000000E+00   0.501964151E-01   0.000000000E+00
      5   0.197115731E-11   0.000000000E+00   0.274866983E-01   0.000000000E+00   0.123067335E+00   0.000000000E+00
      6   0.140794920E-11   0.000000000E+00  -0.224915930E-02   0.000000000E+00   0.132999361E+00   0.000000000E+00
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      7   0.640215607E-12   0.000000000E+00  -0.288603924E-01   0.000000000E+00   0.966436029E-01   0.000000000E+00
      8  -0.408407031E-12   0.000000000E+00  -0.416770861E-01   0.000000000E+00   0.143773606E-01   0.000000000E+00
      9  -0.227912612E-11   0.000000000E+00  -0.277862092E-01   0.000000000E+00  -0.127927180E+00   0.000000000E+00
     10  -0.498594270E-11   0.000000000E+00   0.170955196E-01   0.000000000E+00  -0.230068698E+00   0.000000000E+00
     11  -0.563071325E-11   0.000000000E+00   0.526619157E-01   0.000000000E+00  -0.352910307E-01   0.000000000E+00
     12  -0.277721210E-11   0.000000000E+00   0.358668932E-01   0.000000000E+00   0.171946570E+00   0.000000000E+00
     13   0.325002956E-12   0.000000000E+00  -0.858189396E-02   0.000000000E+00   0.191771938E+00   0.000000000E+00
     14   0.260980914E-11   0.000000000E+00  -0.404677356E-01   0.000000000E+00   0.717904155E-01   0.000000000E+00
     15   0.349405421E-11   0.000000000E+00  -0.382571294E-01   0.000000000E+00  -0.914575797E-01   0.000000000E+00
     16   0.388797339E-11   0.000000000E+00  -0.329032651E-02   0.000000000E+00  -0.202489911E+00   0.000000000E+00
     17   0.481930904E-11   0.000000000E+00   0.455931817E-01   0.000000000E+00  -0.205587429E+00   0.000000000E+00
     18   0.488319736E-11   0.000000000E+00   0.661636912E-01   0.000000000E+00   0.427611300E-01   0.000000000E+00
     19   0.439678713E-11   0.000000000E+00  -0.112608933E-01   0.000000000E+00   0.576830200E+00   0.000000000E+00
     20   0.411328889E-11   0.000000000E+00  -0.237253460E+00   0.000000000E+00   0.122096404E+01   0.000000000E+00
$MODE         11
  0.53349915E+03    0.10000000E+01
      1  -0.520987930E-01   0.000000000E+00  -0.717624578E-11   0.000000000E+00  -0.427623856E-10   0.000000000E+00
      2  -0.470494357E-01   0.000000000E+00   0.268427593E-12   0.000000000E+00  -0.138335596E-10   0.000000000E+00
      3  -0.412239337E-01   0.000000000E+00   0.210575458E-11   0.000000000E+00  -0.123724094E-11   0.000000000E+00
      4  -0.352739743E-01   0.000000000E+00   0.168186330E-11   0.000000000E+00   0.478409202E-11   0.000000000E+00
      5  -0.273221947E-01   0.000000000E+00   0.407360712E-12   0.000000000E+00   0.603236544E-11   0.000000000E+00
      6  -0.154114742E-01   0.000000000E+00  -0.816809439E-12   0.000000000E+00   0.442230375E-11   0.000000000E+00
      7  -0.581571644E-04   0.000000000E+00  -0.146843263E-11   0.000000000E+00   0.116881070E-11   0.000000000E+00
      8   0.192237676E-01   0.000000000E+00  -0.121940200E-11   0.000000000E+00  -0.323256721E-11   0.000000000E+00
      9   0.490069645E-01   0.000000000E+00   0.120748096E-12   0.000000000E+00  -0.776468237E-11   0.000000000E+00
     10   0.771073026E-01   0.000000000E+00   0.183667626E-11   0.000000000E+00  -0.570353425E-11   0.000000000E+00
     11   0.381197682E-01   0.000000000E+00   0.165354768E-11   0.000000000E+00   0.719571145E-11   0.000000000E+00
     12  -0.203233791E-01   0.000000000E+00  -0.446340291E-12   0.000000000E+00   0.925824642E-11   0.000000000E+00
     13  -0.491915537E-01   0.000000000E+00  -0.190938023E-11   0.000000000E+00   0.265663269E-11   0.000000000E+00
     14  -0.498990072E-01   0.000000000E+00  -0.175664917E-11   0.000000000E+00  -0.348692424E-11   0.000000000E+00
     15  -0.307837636E-01   0.000000000E+00  -0.525151547E-12   0.000000000E+00  -0.742674091E-11   0.000000000E+00
     16   0.513839656E-03   0.000000000E+00   0.128075586E-11   0.000000000E+00  -0.737346979E-11   0.000000000E+00
     17   0.295238227E-01   0.000000000E+00   0.213354145E-11   0.000000000E+00   0.582662825E-12   0.000000000E+00
     18   0.538264207E-01   0.000000000E+00  -0.307549983E-12   0.000000000E+00   0.190692553E-10   0.000000000E+00
     19   0.785773236E-01   0.000000000E+00  -0.648043904E-11   0.000000000E+00   0.295822210E-10   0.000000000E+00
     20   0.852269510E-01   0.000000000E+00  -0.106159918E-10   0.000000000E+00   0.128297674E-10   0.000000000E+00
$MODE         12
  0.59547469E+03    0.10000000E+01
      1   0.218712018E-12   0.000000000E+00  -0.178223671E+00   0.000000000E+00  -0.120264339E+01   0.000000000E+00
      2   0.192315334E-12   0.000000000E+00   0.246844734E-01   0.000000000E+00  -0.305127524E+00   0.000000000E+00
      3   0.162466513E-12   0.000000000E+00   0.572494700E-01   0.000000000E+00   0.395917729E-01   0.000000000E+00
      4   0.132555620E-12   0.000000000E+00   0.326940434E-01   0.000000000E+00   0.163598248E+00   0.000000000E+00
      5   0.934926522E-13   0.000000000E+00  -0.465121283E-02   0.000000000E+00   0.150479997E+00   0.000000000E+00
      6   0.368956526E-13   0.000000000E+00  -0.306658213E-01   0.000000000E+00   0.698535271E-01   0.000000000E+00
      7  -0.321556576E-13   0.000000000E+00  -0.347124026E-01   0.000000000E+00  -0.351050571E-01   0.000000000E+00
      8  -0.111449079E-12   0.000000000E+00  -0.140093081E-01   0.000000000E+00  -0.138343166E+00   0.000000000E+00
      9  -0.213934597E-12   0.000000000E+00   0.252841779E-01   0.000000000E+00  -0.181718215E+00   0.000000000E+00
     10  -0.246124043E-12   0.000000000E+00   0.493518835E-01   0.000000000E+00  -0.495737920E-02   0.000000000E+00
     11   0.500788439E-13   0.000000000E+00   0.129242551E-01   0.000000000E+00   0.265881828E+00   0.000000000E+00
     12   0.208491790E-12   0.000000000E+00  -0.384483544E-01   0.000000000E+00   0.126108986E+00   0.000000000E+00
     13   0.171458914E-12   0.000000000E+00  -0.402267525E-01   0.000000000E+00  -0.112594255E+00   0.000000000E+00
     14   0.495388250E-13   0.000000000E+00  -0.112021232E-02   0.000000000E+00  -0.202719195E+00   0.000000000E+00
     15  -0.158618655E-12   0.000000000E+00   0.366635157E-01   0.000000000E+00  -0.103181285E+00   0.000000000E+00
     16  -0.155860286E-11   0.000000000E+00   0.379202394E-01   0.000000000E+00   0.938637631E-01   0.000000000E+00
     17  -0.402682046E-11   0.000000000E+00  -0.748981508E-02   0.000000000E+00   0.272493862E+00   0.000000000E+00
     18  -0.562766128E-11   0.000000000E+00  -0.684391488E-01   0.000000000E+00   0.192271767E+00   0.000000000E+00
     19  -0.669693418E-11   0.000000000E+00  -0.322020555E-01   0.000000000E+00  -0.490958021E+00   0.000000000E+00
     20  -0.668051788E-11   0.000000000E+00   0.259764053E+00   0.000000000E+00  -0.170453825E+01   0.000000000E+00
$MODE         13
  0.66563269E+03    0.10000000E+01
      1  -0.598871174E-01   0.000000000E+00   0.325063432E-11   0.000000000E+00   0.248494458E-10   0.000000000E+00
      2  -0.508517948E-01   0.000000000E+00  -0.806805706E-12   0.000000000E+00   0.447729039E-11   0.000000000E+00
      3  -0.408944693E-01   0.000000000E+00  -0.107337265E-11   0.000000000E+00  -0.227408106E-11   0.000000000E+00
      4  -0.311759842E-01   0.000000000E+00  -0.345763140E-12   0.000000000E+00  -0.370211709E-11   0.000000000E+00
      5  -0.188684246E-01   0.000000000E+00   0.376325134E-12   0.000000000E+00  -0.233332761E-11   0.000000000E+00
      6  -0.182756833E-02   0.000000000E+00   0.666308826E-12   0.000000000E+00  -0.108354547E-12   0.000000000E+00
      7   0.173802587E-01   0.000000000E+00   0.445140041E-12   0.000000000E+00   0.196393178E-11   0.000000000E+00
      8   0.365296267E-01   0.000000000E+00  -0.166526807E-12   0.000000000E+00   0.313330280E-11   0.000000000E+00
      9   0.534611827E-01   0.000000000E+00  -0.785764187E-12   0.000000000E+00   0.185192766E-11   0.000000000E+00
     10   0.329297519E-01   0.000000000E+00  -0.616884416E-12   0.000000000E+00  -0.313512125E-11   0.000000000E+00
     11  -0.626062167E-01   0.000000000E+00   0.465776331E-12   0.000000000E+00  -0.434018273E-11   0.000000000E+00
     12  -0.509136270E-01   0.000000000E+00   0.884792383E-12   0.000000000E+00   0.120668784E-11   0.000000000E+00
     13   0.183053797E-02   0.000000000E+00   0.228443197E-12   0.000000000E+00   0.379522872E-11   0.000000000E+00
     14   0.411837514E-01   0.000000000E+00  -0.438849308E-12   0.000000000E+00   0.126986168E-11   0.000000000E+00
     15   0.512379403E-01   0.000000000E+00  -0.452221602E-12   0.000000000E+00  -0.306167175E-13   0.000000000E+00
     16   0.297080371E-01   0.000000000E+00  -0.617265464E-12   0.000000000E+00   0.125589293E-11   0.000000000E+00
     17  -0.658405777E-02   0.000000000E+00  -0.776625335E-12   0.000000000E+00  -0.806311182E-12   0.000000000E+00
     18  -0.437091415E-01   0.000000000E+00   0.719711117E-12   0.000000000E+00  -0.124193987E-10   0.000000000E+00
     19  -0.863757044E-01   0.000000000E+00   0.499024591E-11   0.000000000E+00  -0.185246592E-10   0.000000000E+00
     20  -0.983169796E-01   0.000000000E+00   0.465124614E-11   0.000000000E+00   0.115265702E-10   0.000000000E+00
$MODE         14
  0.73973021E+03    0.10000000E+01
      1   0.623401668E-12   0.000000000E+00   0.164577292E+00   0.000000000E+00   0.142421921E+01   0.000000000E+00
      2   0.507233060E-12   0.000000000E+00  -0.595328874E-01   0.000000000E+00   0.145208740E+00   0.000000000E+00
      3   0.383134119E-12   0.000000000E+00  -0.516053639E-01   0.000000000E+00  -0.202978188E+00   0.000000000E+00
      4   0.265812957E-12   0.000000000E+00  -0.966555370E-03   0.000000000E+00  -0.207334911E+00   0.000000000E+00
      5   0.122829983E-12   0.000000000E+00   0.333090928E-01   0.000000000E+00  -0.752565081E-01   0.000000000E+00
      6  -0.637992816E-13   0.000000000E+00   0.345619965E-01   0.000000000E+00   0.657758413E-01   0.000000000E+00
      7  -0.252057428E-12   0.000000000E+00   0.839109571E-02   0.000000000E+00   0.153615086E+00   0.000000000E+00
      8  -0.399537675E-12   0.000000000E+00  -0.277984675E-01   0.000000000E+00   0.146910241E+00   0.000000000E+00
      9  -0.419344359E-12   0.000000000E+00  -0.427184099E-01   0.000000000E+00  -0.266811368E-01   0.000000000E+00
     10   0.720323078E-13   0.000000000E+00  -0.203744862E-02   0.000000000E+00  -0.275253366E+00   0.000000000E+00
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     11   0.784909708E-12   0.000000000E+00   0.475775318E-01   0.000000000E+00  -0.522492914E-01   0.000000000E+00
     12   0.631339152E-13   0.000000000E+00   0.228672363E-01   0.000000000E+00   0.235059036E+00   0.000000000E+00
     13  -0.503440936E-12   0.000000000E+00  -0.289238623E-01   0.000000000E+00   0.161189857E+00   0.000000000E+00
     14  -0.516379796E-12   0.000000000E+00  -0.393486823E-01   0.000000000E+00  -0.797856801E-01   0.000000000E+00
     15  -0.745226224E-12   0.000000000E+00  -0.191635831E-02   0.000000000E+00  -0.216358182E+00   0.000000000E+00
     16  -0.158749913E-11   0.000000000E+00   0.406007987E-01   0.000000000E+00  -0.122715154E+00   0.000000000E+00
     17  -0.222856100E-11   0.000000000E+00   0.360176800E-01   0.000000000E+00   0.153346499E+00   0.000000000E+00
     18  -0.216965467E-11   0.000000000E+00  -0.376722469E-01   0.000000000E+00   0.385209535E+00   0.000000000E+00
     19  -0.966811998E-12   0.000000000E+00  -0.683162434E-01   0.000000000E+00  -0.215492605E+00   0.000000000E+00
     20  -0.885400042E-12   0.000000000E+00   0.250686029E+00   0.000000000E+00  -0.202285634E+01   0.000000000E+00
$MODE        15
  0.80825867E+03    0.10000000E+01
      1  -0.715220944E-01   0.000000000E+00  -0.203287182E-11   0.000000000E+00  -0.195501042E-10   0.000000000E+00
      2  -0.556116635E-01   0.000000000E+00   0.943692989E-12   0.000000000E+00  -0.673811517E-12   0.000000000E+00
      3  -0.391683053E-01   0.000000000E+00   0.568648917E-12   0.000000000E+00   0.349558960E-11   0.000000000E+00
      4  -0.241300421E-01   0.000000000E+00  -0.188989158E-12   0.000000000E+00   0.259059524E-11   0.000000000E+00
      5  -0.656240701E-02   0.000000000E+00  -0.530050051E-12   0.000000000E+00   0.201623777E-12   0.000000000E+00
      6   0.148617360E-01   0.000000000E+00  -0.356735893E-12   0.000000000E+00  -0.165213863E-11   0.000000000E+00
      7   0.335969301E-01   0.000000000E+00   0.116883910E-12   0.000000000E+00  -0.229519899E-11   0.000000000E+00
      8   0.429760429E-01   0.000000000E+00   0.540183612E-12   0.000000000E+00  -0.120196258E-11   0.000000000E+00
      9   0.275680182E-01   0.000000000E+00   0.434800159E-12   0.000000000E+00   0.202028472E-11   0.000000000E+00
     10  -0.454121438E-01   0.000000000E+00  -0.367643493E-12   0.000000000E+00   0.382239253E-11   0.000000000E+00
     11  -0.548368695E-01   0.000000000E+00  -0.647957217E-12   0.000000000E+00  -0.208227143E-11   0.000000000E+00
     12   0.406625591E-01   0.000000000E+00   0.157960394E-12   0.000000000E+00  -0.368777457E-11   0.000000000E+00
     13   0.539444140E-01   0.000000000E+00   0.650783894E-12   0.000000000E+00  -0.668956012E-13   0.000000000E+00
     14   0.100174861E-01   0.000000000E+00   0.345962473E-12   0.000000000E+00   0.209784213E-11   0.000000000E+00
     15  -0.386338661E-01   0.000000000E+00   0.127602826E-12   0.000000000E+00  -0.132526649E-11   0.000000000E+00
     16  -0.521594097E-01   0.000000000E+00   0.966321412E-12   0.000000000E+00  -0.506979531E-11   0.000000000E+00
     17  -0.228054840E-01   0.000000000E+00   0.183423832E-11   0.000000000E+00  -0.104623117E-11   0.000000000E+00
     18   0.224958651E-01   0.000000000E+00  -0.789321163E-13   0.000000000E+00   0.170679651E-10   0.000000000E+00
     19   0.853075621E-01   0.000000000E+00  -0.511639509E-11   0.000000000E+00   0.149864981E-10   0.000000000E+00
     20   0.103917364E+00   0.000000000E+00   0.355462486E-11   0.000000000E+00  -0.654069940E-10   0.000000000E+00
$MODE        16
  0.90414831E+03    0.10000000E+01
      1  -0.332944307E-10   0.000000000E+00   0.125334885E+00   0.000000000E+00   0.137791649E+01   0.000000000E+00
      2  -0.240262867E-10   0.000000000E+00  -0.751856645E-01   0.000000000E+00  -0.772672124E-01   0.000000000E+00
      3  -0.149440037E-10   0.000000000E+00  -0.247078657E-01   0.000000000E+00  -0.299777496E+00   0.000000000E+00
      4  -0.708482188E-11   0.000000000E+00   0.305297149E-01   0.000000000E+00  -0.137255026E+00   0.000000000E+00
      5   0.145218351E-11   0.000000000E+00   0.394298929E-01   0.000000000E+00   0.663402445E-01   0.000000000E+00
      6   0.106229116E-10   0.000000000E+00   0.112463986E-01   0.000000000E+00   0.166051094E+00   0.000000000E+00
      7   0.163575296E-10   0.000000000E+00  -0.250646439E-01   0.000000000E+00   0.133547977E+00   0.000000000E+00
      8   0.149425062E-10   0.000000000E+00  -0.385109017E-01   0.000000000E+00  -0.226453139E-01   0.000000000E+00
      9  -0.208459461E-11   0.000000000E+00  -0.418034624E-02   0.000000000E+00  -0.241008580E+00   0.000000000E+00
     10  -0.326763381E-10   0.000000000E+00   0.489559192E-01   0.000000000E+00  -0.134165841E+00   0.000000000E+00
     11   0.211887308E-10   0.000000000E+00   0.178658069E-01   0.000000000E+00   0.327640327E+00   0.000000000E+00
     12   0.980059780E-11   0.000000000E+00  -0.444205781E-01   0.000000000E+00   0.102133020E+00   0.000000000E+00
     13  -0.139245277E-10   0.000000000E+00  -0.271860198E-01   0.000000000E+00  -0.227653646E+00   0.000000000E+00
     14  -0.146958078E-10   0.000000000E+00   0.282008192E-01   0.000000000E+00  -0.189976249E+00   0.000000000E+00
     15   0.178835967E-11   0.000000000E+00   0.402077470E-01   0.000000000E+00   0.100347843E+00   0.000000000E+00
     16   0.163109447E-10   0.000000000E+00  -0.837042620E-02   0.000000000E+00   0.276936692E+00   0.000000000E+00
     17   0.129854541E-10   0.000000000E+00  -0.590080070E-01   0.000000000E+00   0.114842015E+00   0.000000000E+00
     18   0.147995331E-12   0.000000000E+00  -0.136596665E-01   0.000000000E+00  -0.430978297E+00   0.000000000E+00
     19  -0.229438739E-10   0.000000000E+00   0.902409263E-01   0.000000000E+00  -0.186169207E+00   0.000000000E+00
     20  -0.293099927E-10   0.000000000E+00  -0.215538698E+00   0.000000000E+00   0.213539382E+01   0.000000000E+00
$MODE        17
  0.90787455E+03    0.10000000E+01
      1  -0.839427312E-01   0.000000000E+00  -0.487014235E-10   0.000000000E+00  -0.538048128E-09   0.000000000E+00
      2  -0.603827062E-01   0.000000000E+00   0.294652998E-10   0.000000000E+00   0.319860534E-10   0.000000000E+00
      3  -0.373469083E-01   0.000000000E+00   0.941265880E-11   0.000000000E+00   0.117703360E-09   0.000000000E+00
      4  -0.174605900E-01   0.000000000E+00  -0.121466584E-10   0.000000000E+00   0.527814891E-10   0.000000000E+00
      5   0.407151877E-02   0.000000000E+00  -0.153762259E-10   0.000000000E+00  -0.271013874E-10   0.000000000E+00
      6   0.270648429E-01   0.000000000E+00  -0.415730028E-11   0.000000000E+00  -0.653667577E-10   0.000000000E+00
      7   0.411731231E-01   0.000000000E+00   0.100020659E-10   0.000000000E+00  -0.514371128E-10   0.000000000E+00
      8   0.370229784E-01   0.000000000E+00   0.149561566E-10   0.000000000E+00   0.105479229E-10   0.000000000E+00
      9  -0.666907253E-02   0.000000000E+00   0.120607713E-11   0.000000000E+00   0.949928022E-10   0.000000000E+00
     10  -0.825642535E-01   0.000000000E+00  -0.192917000E-10   0.000000000E+00   0.495532968E-10   0.000000000E+00
     11   0.582848864E-01   0.000000000E+00  -0.642647038E-11   0.000000000E+00  -0.129319550E-09   0.000000000E+00
     12   0.206726952E-01   0.000000000E+00   0.176203169E-10   0.000000000E+00  -0.363410119E-10   0.000000000E+00
     13  -0.390250305E-01   0.000000000E+00   0.100602082E-10   0.000000000E+00   0.914963215E-10   0.000000000E+00
     14  -0.355515062E-01   0.000000000E+00  -0.117699431E-10   0.000000000E+00   0.734857253E-10   0.000000000E+00
     15   0.832947839E-02   0.000000000E+00  -0.161650620E-10   0.000000000E+00  -0.403681420E-10   0.000000000E+00
     16   0.426456286E-01   0.000000000E+00   0.288529800E-11   0.000000000E+00  -0.107700692E-09   0.000000000E+00
     17   0.313579682E-01   0.000000000E+00   0.224189865E-10   0.000000000E+00  -0.436450115E-10   0.000000000E+00
     18  -0.386646183E-02   0.000000000E+00   0.490568016E-11   0.000000000E+00   0.164188125E-09   0.000000000E+00
     19  -0.626188342E-01   0.000000000E+00  -0.335867572E-10   0.000000000E+00   0.637454968E-10   0.000000000E+00
     20  -0.808972379E-01   0.000000000E+00   0.843949901E-10   0.000000000E+00  -0.819875750E-09   0.000000000E+00
$MODE        18
  0.10390886E+04    0.10000000E+01
      1  -0.381985599E-01   0.000000000E+00   0.206093278E-11   0.000000000E+00   0.268169994E-10   0.000000000E+00
      2  -0.241544852E-01   0.000000000E+00  -0.161152125E-11   0.000000000E+00  -0.466944237E-11   0.000000000E+00
      3  -0.115928496E-01   0.000000000E+00  -0.587344645E-13   0.000000000E+00  -0.662633733E-11   0.000000000E+00
      4  -0.174435744E-02   0.000000000E+00   0.918430663E-12   0.000000000E+00  -0.960592167E-12   0.000000000E+00
      5   0.753874281E-02   0.000000000E+00   0.631698247E-12   0.000000000E+00   0.326165856E-11   0.000000000E+00
      6   0.149135160E-01   0.000000000E+00  -0.215683181E-12   0.000000000E+00   0.360252047E-11   0.000000000E+00
      7   0.149233153E-01   0.000000000E+00  -0.752101605E-12   0.000000000E+00   0.793126296E-12   0.000000000E+00
      8   0.455726230E-02   0.000000000E+00  -0.436520411E-12   0.000000000E+00  -0.327788358E-11   0.000000000E+00
      9  -0.207025921E-01   0.000000000E+00   0.621918407E-12   0.000000000E+00  -0.466472245E-11   0.000000000E+00
     10  -0.201563243E-01   0.000000000E+00   0.853956422E-12   0.000000000E+00   0.314067350E-11   0.000000000E+00
     11   0.689462681E-01   0.000000000E+00  -0.642683344E-12   0.000000000E+00   0.525152168E-11   0.000000000E+00
     12  -0.804541950E-01   0.000000000E+00  -0.747726558E-12   0.000000000E+00  -0.461205783E-11   0.000000000E+00
     13  -0.114965471E-01   0.000000000E+00   0.603157420E-12   0.000000000E+00  -0.513190701E-11   0.000000000E+00
     14   0.606565325E-01   0.000000000E+00   0.118607804E-11   0.000000000E+00   0.350004943E-13   0.000000000E+00
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      15   0.345365473E-01   0.000000000E+00   0.757972175E-12   0.000000000E+00   0.321694225E-11   0.000000000E+00
      16  -0.434486336E-01   0.000000000E+00   0.375793938E-13   0.000000000E+00   0.244101256E-11   0.000000000E+00
      17  -0.584030717E-01   0.000000000E+00   0.337831592E-14   0.000000000E+00  -0.220428652E-11   0.000000000E+00
      18  -0.189565641E-01   0.000000000E+00   0.107177610E-11   0.000000000E+00  -0.414191065E-11   0.000000000E+00
      19   0.757526774E-01   0.000000000E+00   0.387038388E-12   0.000000000E+00   0.823502993E-11   0.000000000E+00
      20   0.107599730E+00   0.000000000E+00  -0.335980676E-11   0.000000000E+00   0.209078366E-10   0.000000000E+00
$MODE         19
  0.11032624E+04     0.10000000E+01
       1   0.231211682E-12   0.000000000E+00   0.955760030E-01   0.000000000E+00   0.134573620E+01   0.000000000E+00
       2   0.135399733E-12   0.000000000E+00  -0.829591652E-01   0.000000000E+00  -0.306548544E+00   0.000000000E+00
       3   0.539950522E-13   0.000000000E+00   0.688180292E-02   0.000000000E+00  -0.337237007E+00   0.000000000E+00
       4  -0.629919366E-14   0.000000000E+00   0.506164822E-01   0.000000000E+00   0.974114842E-03   0.000000000E+00
       5  -0.580289599E-13   0.000000000E+00   0.253397063E-01   0.000000000E+00   0.199820841E+00   0.000000000E+00
       6  -0.895068062E-13   0.000000000E+00  -0.202311116E-01   0.000000000E+00   0.166256378E+00   0.000000000E+00
       7  -0.693306731E-13   0.000000000E+00  -0.389942460E-01   0.000000000E+00  -0.145004327E-01   0.000000000E+00
       8   0.104095474E-13   0.000000000E+00  -0.104605988E-01   0.000000000E+00  -0.210462537E+00   0.000000000E+00
       9   0.145254918E-12   0.000000000E+00   0.421222417E-01   0.000000000E+00  -0.179101250E+00   0.000000000E+00
      10   0.920426641E-14   0.000000000E+00   0.278094353E-01   0.000000000E+00   0.277772123E+00   0.000000000E+00
      11  -0.277893206E-12   0.000000000E+00  -0.480746086E-01   0.000000000E+00   0.129108787E+00   0.000000000E+00
      12   0.483905712E-12   0.000000000E+00  -0.183507940E-01   0.000000000E+00  -0.318504844E+00   0.000000000E+00
      13  -0.156943665E-12   0.000000000E+00   0.429295671E-01   0.000000000E+00  -0.105169157E+00   0.000000000E+00
      14  -0.356772071E-12   0.000000000E+00   0.239952885E-01   0.000000000E+00   0.240439694E+00   0.000000000E+00
      15   0.457798936E-12   0.000000000E+00  -0.336434941E-01   0.000000000E+00   0.178349585E+00   0.000000000E+00
      16   0.168264426E-11   0.000000000E+00  -0.339347162E-01   0.000000000E+00  -0.179859601E+00   0.000000000E+00
      17   0.144648389E-11   0.000000000E+00   0.397806947E-01   0.000000000E+00  -0.357390382E+00   0.000000000E+00
      18  -0.200890190E-12   0.000000000E+00   0.596419683E-01   0.000000000E+00   0.234987673E+00   0.000000000E+00
      19  -0.222667632E-11   0.000000000E+00  -0.844376389E-01   0.000000000E+00   0.546335919E+00   0.000000000E+00
      20  -0.312059235E-11   0.000000000E+00   0.147829284E+00   0.000000000E+00  -0.182451038E+01   0.000000000E+00
$MODE         20
  0.11652801E+04     0.10000000E+01
       1  -0.146457417E+00   0.000000000E+00  -0.624763938E-13   0.000000000E+00  -0.938426738E-12   0.000000000E+00
       2  -0.787380349E-01   0.000000000E+00   0.591268408E-13   0.000000000E+00   0.257904317E-12   0.000000000E+00
       3  -0.243096006E-01   0.000000000E+00  -0.111525907E-13   0.000000000E+00   0.238046205E-12   0.000000000E+00
       4   0.134127659E-01   0.000000000E+00  -0.380860091E-13   0.000000000E+00  -0.283874536E-13   0.000000000E+00
       5   0.422759773E-01   0.000000000E+00  -0.130277374E-13   0.000000000E+00  -0.166543964E-12   0.000000000E+00
       6   0.530324532E-01   0.000000000E+00   0.211087303E-13   0.000000000E+00  -0.106343014E-12   0.000000000E+00
       7   0.285583765E-01   0.000000000E+00   0.272411104E-13   0.000000000E+00   0.571505744E-13   0.000000000E+00
       8  -0.271388138E-01   0.000000000E+00  -0.190537348E-14   0.000000000E+00   0.175331166E-12   0.000000000E+00
       9  -0.884122641E-01   0.000000000E+00  -0.353360425E-13   0.000000000E+00   0.700803373E-13   0.000000000E+00
      10   0.654305809E-01   0.000000000E+00  -0.691537205E-14   0.000000000E+00  -0.250980406E-12   0.000000000E+00
      11  -0.212432452E-01   0.000000000E+00   0.375848807E-13   0.000000000E+00   0.312064551E-13   0.000000000E+00
      12  -0.141823831E-03   0.000000000E+00  -0.807011430E-14   0.000000000E+00   0.256806514E-12   0.000000000E+00
      13   0.147990499E-01   0.000000000E+00  -0.465389780E-13   0.000000000E+00   0.445513738E-13   0.000000000E+00
      14  -0.457838050E-02   0.000000000E+00  -0.490059475E-13   0.000000000E+00   0.787511121E-13   0.000000000E+00
      15  -0.133786661E-01   0.000000000E+00  -0.727860018E-13   0.000000000E+00   0.382708969E-14   0.000000000E+00
      16   0.309569574E-02   0.000000000E+00  -0.374566597E-13   0.000000000E+00  -0.249723139E-12   0.000000000E+00
      17   0.132833304E-01   0.000000000E+00  -0.480976695E-14   0.000000000E+00   0.669040944E-13   0.000000000E+00
      18   0.846620429E-02   0.000000000E+00  -0.137900314E-12   0.000000000E+00   0.851814958E-12   0.000000000E+00
      19  -0.139220296E-01   0.000000000E+00  -0.229202915E-12   0.000000000E+00  -0.462501861E-12   0.000000000E+00
      20  -0.221770246E-01   0.000000000E+00   0.641007742E-12   0.000000000E+00  -0.558205150E-11   0.000000000E+00
```

Listing 8.7.4 Output of Mass change due to Structure: masschng.dat

```
0.00000000         0.35151434E+00
0.22458947         0.15923738E+01
0.44917893         0.34992027E+01
0.67376840         0.47900314E+01
0.89835787         0.47755566E+01
1.12294734         0.42759323E+01
1.34753680         0.36480141E+01
1.57212627         0.24694061E+01
1.79671574         0.12667809E+01
2.02130532         0.63976669E+00
2.24589467         0.55348587E+00
2.47048426         0.80759811E+00
2.69507360         0.11092186E+01
2.91966319         0.13285332E+01
3.14425254         0.13999634E+01
3.36884212         0.14529495E+01
3.59343147         0.14412441E+01
3.81802106         0.10710030E+01
4.04261065         0.59553242E+00
4.26719999         0.21292615E+00
```

8.8 Run UCDA to get TRIM and ASE Solution

This section corresponds to the Step 6 in the Graphical User Interface (GUI). See Figure 8.8.1 below.

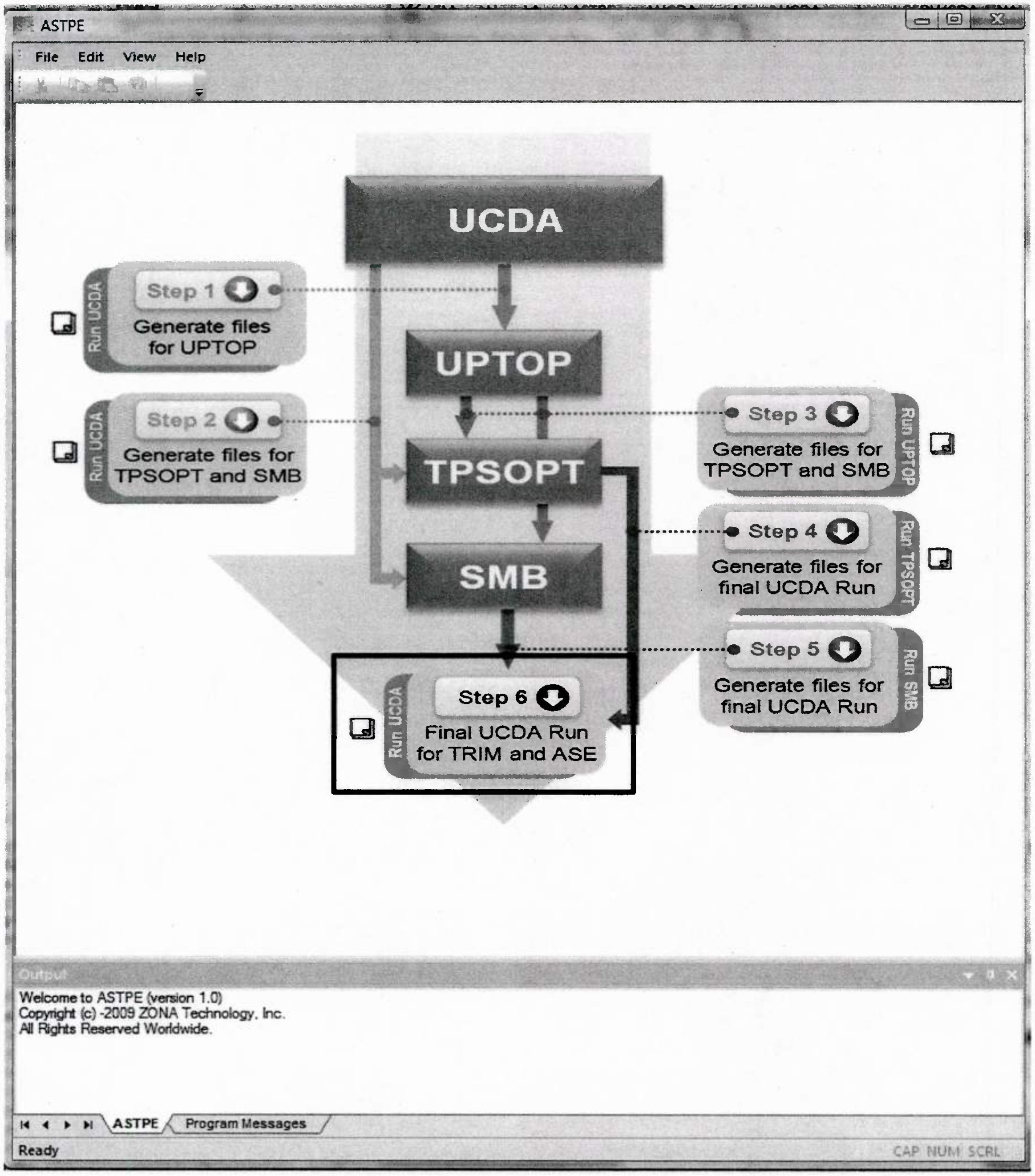


Figure 8.8.1 Section Corresponding to Step 6 of GUI

Input Files:

File Name	Type	Remarks	See Listing
vehicle.inp	Standard input file	Also look at Table 8.8.1	Shown in Listing 8.8.1
chem.bin	Engine chemistry information	Required	Shown in Listing 8.2.2
mass_tps.dat	Generated by TPSOPT	ifeedback needs to be 1	Shown in Listing 8.8.2
masschng.dat	Generated by SMB	ifeedback needs to be 1	Shown in Listing 8.8.3
RDOF_EIGEN.FREE	Generated by SMB	ifeedback needs to be 1	Shown in Listing 8.8.4

Output Files:

File Name	Type	Remarks	See Listing
trim_output.dat	Trim results by UCDA	See Fig. 8.8.2	Shown in Listing 8.8.5
Prep_ASE.dat	ASE results by UCDA	See Tables 8.8.2-8.8.3	Shown in Listing 8.8.6

Input File Descriptions

vehicle.inp: See Listing 8.8.1 for the entire input file. Also, Table 8.8.1 shows the necessary block and change in input parameters therein. The user should turn on **itrim** so that UCDA includes control surface in its calculation. **ideriv** is the input switch parameter that is to be set to **1** for running TRIM and ASE. **itps** should be turned back to **0** so that TPS geometry information is not created and in the process that saves some computational run time. Finally, **ifeedback** should be turned on to include the mass update from TPS and SMB. The user should note at this point that before this step, **ifeedback** was always set to **0**. That is because before this step, TPSOPT and SMB was never run (look at Figure 8.8.1). This step finishes one design cycle. After this step, for all the subsequent design cycles, this **ifeedback** parameter should ALWAYS be set to **1**. The code internally keeps track of the mass for each design cycle and that needs **ifeedback** to be set to **1**. If **ifeedback** value is set to **0** by mistake, the mass information is not going to be right.

Table 8.8.1: Showing Necessary Block on Vehicle.inp to Compute TRIM and ASE

TEST INPUT DECK: Note - this line must be here!	
2	ialtdyn - Inlet specified alt. (0), Fixed alt. (1), or Fixed dyn. press. (2)
1	ithrottle - Run engine as a function of: (0) equivalence ratio, (1) % throttle
1	iunits - Output unit switch: SI (1) or English (2)
3	ivisc - Viscous flag: inviscid (1), laminar (2), transitional (3), turbulent (4)
1	iequiv - find max equiv ratio for choked flow: off (0) -> single run, on (1)
2	inozorder - Nozzle polynomial order: 1st (flat plate) -> 3rd
1	iheight - Height constrained vehicle: no (0) = linlet set, yes (1) = height set
0	itrajectory - Run multiple trajectory points: no (0), discrete (1), matrix (2)
0	icone - cone flow data: exact (0), curve-fit approximation (1)
1	imodel - Forebody type: WA (1), VWA (2), or VWA + cone flow (3)
1	itrim - Control surface deflection to trim the vehicle: no (0), yes (1), or optimize (2)
1	ideriv - Calculate derivatives: no (0), yes (1)
0	itps - If itps is 1, then prepare for tps and smb. ideriv and itps cannot be 1 at one time
1	ifeedback - If 1, then gets weight and Cg information from SMB and TPSOPT

chem.bin: This file does not change for any UCDA run. Please see Section 8.2 for description on this file.

mass_tps.dat: This file is shown in Listing 8.8.2. It is generated by TPSOPT run. More on this can be found in Section 6.

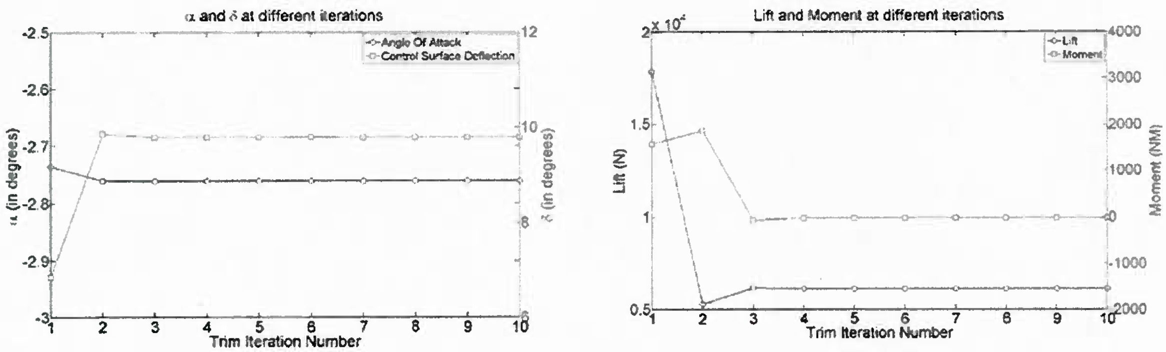
masschng.dat: This file is shown in Listing 8.8.3 and it is generated by SMB run. When UCDA was run to generate the geometry for TPSOPT and SMB that were described in Section 8.5, the structure was approximated by a finite number of discrete points. masschng.dat outputs the additional mass due to skin thickness at each of those points. More on this can be found in Section 8.7.

RDOF_EIGEN.DAT: This file is shown in Listing 8.8.4. It is also generated by SMB run. Natural frequencies and generalized masses of the first 20 modes are recorded in the file. More on this can be found in Section 8.7.

Output File descriptions

Trim_output.dat: This file is shown in Listing 8.8.5. It outputs the summary of information related to trim iterations. Geometric information such as C.G., reference area, reference chord and aerodynamic information such as Coefficients of lift, drag and moment due to change in angle of attack and control surface deflection angle are some of the information. Also, trim variables angle of attack and control surface deflection angles are listed for each iteration.

The iteration history from trim_output.dat file is shown in Figure 8.8.2. It can be seen that this iterative process requires only less than 10 iterations to achieve a fully converged solution. In fact, the mean flow condition in terms of α_0 and δ_0 does not change significantly after 5 iterations. Meanwhile, the lift and moment at the fifth iteration have already nearly satisfied the lift-equal-weight and zero-pitch-moment conditions. From the fifth to the tenth iteration, the trim solution remains nearly the same; indicating that this iterative process is stable and provides a fast converging rate.



(a) Mean Flow Condition (b) Lift and Pitch Moment

Figure 8.8.2 Iteration history of the iterative process for solving the nonlinear trim problem

Prep_ASE.dat: This file is shown in Listing 8.8.6. It outputs the summary of information related to ASE matrix preparation. As shown in the listing, A and B matrices are listed first. Then, the eigenvalues of matrix A is given. Frequency and damping ratio corresponding to the eigenvalues are then output. Finally, other aerodynamic information are written out so that the results can be compared with analytical expressions.

Validation of the ASE module

The validation of the ASE module can be achieved by first excluding the elastic modes then comparing the eigenvalues of the matrix $\left[\bar{A}\right]$ to those of analytical flight dynamic equations shown in the following equations[2]:

For Phugoid mode:

$$\omega_{np} = \frac{\rho SU\sqrt{-C_{L_u}C_{L_o}}}{2m} \tag{8.8.1}$$

$$\zeta_p = \frac{-C_{x_u}}{2\frac{mU}{Sq}\frac{\sqrt{-C_{L_u}C_L}}{mU/Sq}} = \frac{-C_{D_u}}{2\sqrt{-C_{L_u}C_{L_o}}} \tag{8.8.2}$$

For short period mode:

$$\omega = \left(\frac{\frac{c}{2U}C_{m_q}C_{L_\alpha} - \frac{mU}{Sq}C_{m_\alpha}}{\left(\frac{I_y}{Sqc}\right)\left(\frac{mU}{Sq}\right)}\right)^{1/2} \tag{8.8.3}$$

$$\zeta = -\frac{1}{4}\left(C_{m_q} + C_{m_\alpha} + \frac{2I_y}{mc^2}C_{L_\alpha}\right)\left(\frac{mc^2}{I_y\left(\frac{C_{m_q}C_{L_\alpha}}{2} - \frac{2mC_{m_\alpha}}{pSc}\right)}\right)^{1/2} \tag{8.8.4}$$

---

[2] Blakelock, J. H., "Automated Control of Aircraft and Missiles," Air Force Institute of Technology, 1981.

The aerodynamic stability derivatives are computed first on the selected scramjet flight vehicle at the trim condition of $\alpha = -2.76°$, $\delta = 9.79°$. These aerodynamic stability derivatives are shown in Table 8.8.2. Other parameters required by the analytical flight dynamic equations are: mass (m) = 625.6124, moment of inertia (Iy) = 3632.134, velocity (U) = 1777.383, surface area (S) = 1.777043, dynamic pressure (q) = 95729.13 and reference chord (c) = 4.267200 .

Table 8.8.2 Aerodynamic Stability Derivatives of a Scramjet Flight Vehicle

Airframe State	C_D	C_L	C_M
Mean Flow	**8.6021081E-02**	**3.6066845E-02**	**-2.2896980E-05**
Forward Velocity	**1.2826486E-04**	**1.2870191E-04**	**-3.8179856E-05**
Angle of Attack	**-0.6494278**	**2.286335**	**6.1838981E-02**
Pitch Rate	**7.8784697E-02**	**-2.6101999E-02**	**2.4510620E-02**

It can be seen in Table 8.8.2 that the pitch moment stability derivative of angle of attack (C_{m_α}) is positive; indicating a statically unstable flight vehicle.

Two sets of the ASE module of ASTPE are computed, one without the elastic mode (rigid body modes only) and the other with the first bending mode with natural frequency = 9.755 Hz, and compared to the analytical solution. This comparison is presented in Table 8.8.3 where an excellent agreement between the ASE module result without the elastic mode and the analytical solution can be seen. Meanwhile, the ASE module result with the first bending mode shows only a slight difference from that with only the rigid modes. This suggests that the structure designed by the SMB module provides sufficient stiffness by which the impact of aeroelastic effects on the flight dynamics is minimized.

Table 8.8.3 Validation of the ASE module with Analytical Solution

Longitudinal Dynamics	ASTPE				Analytical (Rigid)	
	+ Bending		Rigid			
	Damping	Frequency	Damping	Frequency	Damping	Frequency
Short Period	-1.0	0.3278 (Hz)	-1.0	0.343 (Hz)	-1.0	0.343 (Hz)
Phugoid	0.772	0.00079 (Hz)	0.729	0.00091(Hz)	0.734	0.00091(Hz)

Note that the negative damping of the short period mode is due to the unstable C_{m_α}, leading to a statically unstable flight vehicle that must be stabilized by a flight control system. A flight control system is designed for studied SEM and is given in Figure 8.8.3.

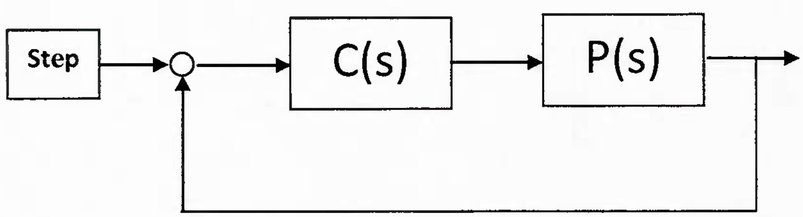


Figure 8.8.3 Block diagram of closed loop system

The compensator $C(s)$ takes the form:

$$C(s) = \frac{-1.489s^6 - 2.299s^5 - 5594s^4 - 8571s^3 - 2292s^2 - 19.15s - 0.07096}{0.001156s^7 + 0.03502s^6 + 5.345s^5 + 131.6s^4 + 3759s^3 + 31.87s^2 + 0.1198s}.$$

Listing 8.8.1: Vehicle.inp Input File for TRIM and ASE

```
TEST INPUT DECK:  Note - this line must be here!
2         ialtdyn - Inlet specified alt. (0), Fixed alt. (1), or Fixed dyn. press. (2)
1         ithrottle - Run engine as a function of: (0) equivalence ratio, (1) % throttle
1         iunits - Output unit switcb: SI (1) or English (2)
3         ivisc - Viscous flag: inviscid (1), laminar (2), transitional (3), turbulent (4)
1         iequiv - find max equiv ratio for choked flow: off (0) -> single run, on (1)
2         inozorder - Nozzle polynomial order: 1st (flat plate) -> 3rd
1         iheight - Height constrained vehicle: no (0) = 1inlet set, yes (1) = height set
0         itrajectory - Run multiple trajectory points: no (0), discrete (1), matrix (2)
0         icone - cone flow data: exact (0), curve-fit approximation (1)
1         imodel - Forebody type: WA (1), VWA (2), or VWA + cone flow (3)
1         itrim - Control surface deflection to trim the vehicle: no (0), yes (1), or optimize (2)
1         ideriv - Calculate derivatives: no (0), yes (1)
0         itps - If itps is 1, then prepare for tps and smb. ideriv and itps cannot be 1 at one time
```

```
1        ifeedback - If 1, then gets weight and Cg information from SMB and TPSOPT

OUTPUT FILE SWITCHES AND NAMES:
1   'plot.dat'                          VEHICLEFIG:         off (0), select (1), x,y,z (2), all (3)
3 1 2 3 8 18 23        1st # -> # of variables to read, others -> vars to plot
1   'metrics.dat'                       METRICS:  off (0), on (1)
0   'cowlexit.dat'                      COWLEXIT:           off (0), on (1)
0   'moc.dat'                           NOZFIG:   off (0), P,T,M (1), all (2)
0   'offdesign.dat'                     AOA:      off (0), on (1), UPTOP input tables (2), UPTOP input files (3)
0   'scramjet.dat'                      CKENGINE: off (0), on (1)
0                                       IPRINTINLET:        off (0), all (1), results (2), all-real (3), results-real (4)
0                                       IPRINTENGINE:       off (0), on (1)
0                                       IDEBUG:           off (0), on (1) [print debugging info]

ZONE DATA AND GRID SIZES:
16       NUMBER OF ZONES
'forebody : top'             31        31
'keel : top'                 101       6
'aftbody : top'              101       31
'forebody : bot'             31        31
'ramps : bot'                55        6
'comb : bot'                 101       6
'cowl : top'                 101       6
'nozzle : bot'               31 .      6
'ramp walls : inside'        35        6
'comb wall : inside'         101       7
'nozzle wall : inside'       21        7
'aftbody : bot'              101       31
'cowl : bot'                 101       6
'ramp walls : outside'       35        6
'comb wall : outside'        101       7
'nozzle wall : outside'      21        7

INPUT DATA:  (0 = degrees, 1 = m, 2 = ft, 3 = atm, 4 = dimensionless, K or kg, 5 = psf)
xl         x         xu      unit      res name
22500.     26000.    30000.    1       2500.         'altitude' - altitude (if required)
2000.      2200.     2400.0    5        200.         'q0'       - dynamic pressure (if required)
.50        1.099     1.0       4       .250          'equiv'    - equivalence ratio
1.         1.        0.0       4       -.05         'throttle' - engine throttle (if required)
6.0        6.00      8.00      4        .5           'm0'       - Mach number
-2.0       -1.0      3.00      0        .5           'AOA'      - angle of attack
6.0        4          'Mdes'      - design Mach number
1.0        0          'AOAdes'    - design angle of attack
21800.     1          'Zdes'      - design altitude
4.2672     1          'lvehicle'  - vehicle length
6.0000     0          'thforclu'  - forebody upper surface angle
5.2797     0          'thforcll'  - forebody ramp angle
0.5873     1          'lcontrol'  - control surface length
7.73       0          'th_control'- control surface deflection angle
0.9920     0          'th_expn'   - nozzle initial expansion angle
10.8958    0          'th_exit'   - nozzle exit angle
0.0        4          'p_nozpoly' - % diff between nozzle designs [DON'T USE-defaulted to 1.]
1.901      1          'lcowl'     - cowl length (isolator/combustor)
.3         1          'lcowlext'  - cowl extension length (internal nozzle)
0.545      4          'p_iso'     - percent of lcowl that is isolator
.3238      1          'height'    - height of vehicle (if required)
20.0       1          'linlet'    - inlet length of vehicle (if required)
.26        1          'wengine'   - width of the engine (currently defaulted to unit width)
3.00       4          'iramps'    - number of inlet ramps in addition to the forebody
6.4012     0          'th_ramp1'  - inlet ramp 1 angle
5.2383     0          'th_ramp2'  - inlet ramp 2 angle
5.5        0          'th_ramp3'  - inlet ramp 3 angle
0.0        0          'th_ramp4'  - inlet ramp 4 angle
0.0        0          'th_ramp5'  - inlet ramp 5 angle
3.09       0          'th_div1'   - first combustor expansion angle
0.2        0          'th_div2'   - second combustor expansion angle
0.01       1          'Xinjs'       - beginning of injectors (m)
0.02       1          'Xinje'     - end of injectors (m)
0.01       1          'Lmix'      - fuel mixing length (m)
1.00       4          'eta_mix'   - fuel mixing and burning efficiency
3000.      4          'Tlimit'    - maximum engine temperature (K)
90.        0          'Thetainj'  - injector angle (degrees) [90 deg. is normal to flow]
1200.      4          'Tw'        - adiabatic wall temperature (K)
0.1527     4          'nfor'      - forebody exponent n
2.0        2          'wfor'      - forebody width
1.5        2          'lfor'      - forebody length
0.2427     4          'mfor'      - forebody exponent m
5.797      0          'thforle'   - forebody leading edge angle
21.519     0          'th_le'     - leading edge attachment angle
0.0000     4          'p_kl'      - keel-line height percentage
0.25       4          'fuelfrac'  - vehicle fuel volume fraction
0.0104     2          't_plate'   - shell plate thickness (Tungsten)
0.0        4          'mass_smb'  - mass due to Structural Modal Base (SMB) analysis
0.0        4        . 'mass_tps'  - mass due to Thermal Protection System (TPS) analysis
0.0        4          'mass_nose' - lumped mass at the nose to manipulate CG
```

Listing 8.8.2 mass_tps.DAT

```
15.65999        34.37291
```

Listing 8.8.3 masschng.dat

```
0.00000000          0.35151434E+00
0.22458947          0.15923738E+01
0.44917893          0.34992027E+01
0.67376840          0.47900314E+01
0.89835787          0.47755566E+01
1.12294734          0.42759323E+01
1.34753680          0.36480141E+01
1.57212627          0.24694061E+01
1.79671574          0.12667809E+01
2.02130532          0.63976669E+00
2.24589467          0.55348587E+00
2.47048426          0.80759811E+00
2.69507360          0.11092186E+01
2.91966319          0.13285332E+01
3.14425254          0.13999634E+01
3.36884212          0.14529495E+01
3.59343147          0.14412441E+01
3.81802106          0.10710030E+01
4.04261065          0.59553242E+00
4.26719999          0.21292615E+00
```

Listing 8.8.4 Eigenvalues and Eigenvectors of the Beam Model: RDOF_EIGEN.FREE

```
 20        20
    1       0.00000000E+00    0.00000000E+00    0.00000000E+00
    2       0.22458947E+00    0.00000000E+00    0.00000000E+00
    3       0.44917893E+00    0.00000000E+00    0.00000000E+00
    4       0.67376840E+00    0.00000000E+00    0.00000000E+00
    5       0.89835787E+00    0.00000000E+00    0.00000000E+00
    6       0.11229473E+01    0.00000000E+00    0.00000000E+00
    7       0.13475368E+01    0.00000000E+00    0.00000000E+00
    8       0.15721263E+01    0.00000000E+00    0.00000000E+00
    9       0.17967157E+01    0.00000000E+00    0.00000000E+00
   10       0.20213053E+01    0.00000000E+00    0.00000000E+00
   11       0.22458947E+01    0.00000000E+00    0.00000000E+00
   12       0.24704843E+01    0.00000000E+00    0.00000000E+00
   13       0.26950736E+01    0.00000000E+00    0.00000000E+00
   14       0.29196632E+01    0.00000000E+00    0.00000000E+00
   15       0.31442525E+01    0.00000000E+00    0.00000000E+00
   16       0.33688421E+01    0.00000000E+00    0.00000000E+00
   17       0.35934315E+01    0.00000000E+00    0.00000000E+00
   18       0.38180211E+01    0.00000000E+00    0.00000000E+00
   19       0.40426106E+01    0.00000000E+00    0.00000000E+00
   20       0.42672000E+01    0.00000000E+00    0.00000000E+00
$MODE        1
  0.57272335E-01    0.10000000E+01
    1  -0.404903816E-01  0.000000000E+00  -0.489255126E-06  0.000000000E+00  -0.380781555E-06  0.000000000E+00
    2  -0.404903815E-01  0.000000000E+00  -0.403735601E-06  0.000000000E+00  -0.380781507E-06  0.000000000E+00
    3  -0.404903807E-01  0.000000000E+00  -0.318216072E-06  0.000000000E+00  -0.380781732E-06  0.000000000E+00
    4  -0.404903819E-01  0.000000000E+00  -0.232696502E-06  0.000000000E+00  -0.380781703E-06  0.000000000E+00
    5  -0.404903830E-01  0.000000000E+00  -0.147176944E-06  0.000000000E+00  -0.380781740E-06  0.000000000E+00
    6  -0.404903877E-01  0.000000000E+00  -0.616573504E-07  0.000000000E+00  -0.380782007E-06  0.000000000E+00
    7  -0.404903890E-01  0.000000000E+00   0.238623523E-07  0.000000000E+00  -0.380782773E-06  0.000000000E+00
    8  -0.404903904E-01  0.000000000E+00   0.109382364E-06  0.000000000E+00  -0.380784766E-06  0.000000000E+00
    9  -0.404903930E-01  0.000000000E+00   0.194903123E-06  0.000000000E+00  -0.380789353E-06  0.000000000E+00
   10  -0.404903979E-01  0.000000000E+00   0.280425505E-06  0.000000000E+00  -0.380798871E-06  0.000000000E+00
   11  -0.404904020E-01  0.000000000E+00   0.365950743E-06  0.000000000E+00  -0.380815229E-06  0.000000000E+00
   12  -0.404904045E-01  0.000000000E+00   0.451479058E-06  0.000000000E+00  -0.380825553E-06  0.000000000E+00
   13  -0.404904080E-01  0.000000000E+00   0.537009134E-06  0.000000000E+00  -0.380831768E-06  0.000000000E+00
   14  -0.404904105E-01  0.000000000E+00   0.622540525E-06  0.000000000E+00  -0.380836751E-06  0.000000000E+00
   15  -0.404904097E-01  0.000000000E+00   0.708073128E-06  0.000000000E+00  -0.380844026E-06  0.000000000E+00
   16  -0.404904088E-01  0.000000000E+00   0.793608045E-06  0.000000000E+00  -0.380856754E-06  0.000000000E+00
   17  -0.404904077E-01  0.000000000E+00   0.879146456E-06  0.000000000E+00  -0.380872712E-06  0.000000000E+00
   18  -0.404904036E-01  0.000000000E+00   0.964687688E-06  0.000000000E+00  -0.380877538E-06  0.000000000E+00
   19  -0.404904012E-01  0.000000000E+00   0.105022596E-05  0.000000000E+00  -0.380854355E-06  0.000000000E+00
   20  -0.404904013E-01  0.000000000E+00   0.113575690E-05  0.000000000E+00  -0.380821590E-06  0.000000000E+00
$MODE        2
  0.27634893E+00    0.10000000E+01
    1   0.504455971E-06  0.000000000E+00  -0.365263016E-01  0.000000000E+00  -0.297418193E-01  0.000000000E+00
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     2   0.504455957E-06   0.000000000E+00  -0.298466060E-01   0.000000000E+00  -0.297417714E-01   0.000000000E+00
     3   0.504455931E-06   0.000000000E+00  -0.231669195E-01   0.000000000E+00  -0.297417532E-01   0.000000000E+00
     4   0.504455930E-06   0.000000000E+00  -0.164872382E-01   0.000000000E+00  -0.297417146E-01   0.000000000E+00
     5   0.504455918E-06   0.000000000E+00  -0.980756673E-02   0.000000000E+00  -0.297416760E-01   0.000000000E+00
     6   0.504455935E-06   0.000000000E+00  -0.312790199E-02   0.000000000E+00  -0.297416534E-01   0.000000000E+00
     7   0.504455885E-06   0.000000000E+00   0.355175883E-02   0.000000000E+00  -0.297416471E-01   0.000000000E+00
     8   0.504455797E-06   0.000000000E+00   0.102314239E-01   0.000000000E+00  -0.297416901E-01   0.000000000E+00
     9   0.504455588E-06   0.000000000E+00   0.169111047E-01   0.000000000E+00  -0.297417751E-01   0.000000000E+00
    10   0.504455073E-06   0.000000000E+00   0.235908069E-01   0.000000000E+00  -0.297418451E-01   0.000000000E+00
    11   0.504453953E-06   0.000000000E+00   0.302705049E-01   0.000000000E+00  -0.297417698E-01   0.000000000E+00
    12   0.504453052E-06   0.000000000E+00   0.369501751E-01   0.000000000E+00  -0.297415578E-01   0.000000000E+00
    13   0.504452379E-06   0.000000000E+00   0.436297890E-01   0.000000000E+00  -0.297413471E-01   0.000000000E+00
    14   0.504451802E-06   0.000000000E+00   0.503093730E-01   0.000000000E+00  -0.297412592E-01   0.000000000E+00
    15   0.504451945E-06   0.000000000E+00   0.569889385E-01   0.000000000E+00  -0.297412056E-01   0.000000000E+00
    16   0.504454070E-06   0.000000000E+00   0.636685025E-01   0.000000000E+00  -0.297412410E-01   0.000000000E+00
    17   0.504454445E-06   0.000000000E+00   0.703480946E-01   0.000000000E+00  -0.297414756E-01   0.000000000E+00
    18   0.504453899E-06   0.000000000E+00   0.770277678E-01   0.000000000E+00  -0.297418286E-01   0.000000000E+00
    19   0.504453831E-06   0.000000000E+00   0.837074998E-01   0.000000000E+00  -0.297420186E-01   0.000000000E+00
    20   0.504456598E-06   0.000000000E+00   0.903872522E-01   0.000000000E+00  -0.297420940E-01   0.000000000E+00
$MODE        3
  0.60200765E+00    0.10000000E+01
     1   0.164771606E-07   0.000000000E+00  -0.841103576E-01   0.000000000E+00  -0.252457161E-01   0.000000000E+00
     2   0.164771586E-07   0.000000000E+00  -0.784404688E-01   0.000000000E+00  -0.252452761E-01   0.000000000E+00
     3   0.164771558E-07   0.000000000E+00  -0.727706762E-01   0.000000000E+00  -0.252449368E-01   0.000000000E+00
     4   0.164771535E-07   0.000000000E+00  -0.671009721E-01   0.000000000E+00  -0.252444755E-01   0.000000000E+00
     5   0.164771500E-07   0.000000000E+00  -0.614313851E-01   0.000000000E+00  -0.252439153E-01   0.000000000E+00
     6   0.164771451E-07   0.000000000E+00  -0.557619279E-01   0.000000000E+00  -0.252433584E-01   0.000000000E+00
     7   0.164771351E-07   0.000000000E+00  -0.500925957E-01   0.000000000E+00  -0.252428250E-01   0.000000000E+00
     8   0.164771187E-07   0.000000000E+00  -0.444233890E-01   0.000000000E+00  -0.252422622E-01   0.000000000E+00
     9   0.164770810E-07   0.000000000E+00  -0.387543284E-01   0.000000000E+00  -0.252415784E-01   0.000000000E+00
    10   0.164769906E-07   0.000000000E+00  -0.330854128E-01   0.000000000E+00  -0.252409723E-01   0.000000000E+00
    11   0.164768044E-07   0.000000000E+00  -0.274165823E-01   0.000000000E+00  -0.252409208E-01   0.000000000E+00
    12   0.164766558E-07   0.000000000E+00  -0.217476885E-01   0.000000000E+00  -0.252413924E-01   0.000000000E+00
    13   0.164765423E-07   0.000000000E+00  -0.160786861E-01   0.000000000E+00  -0.252418976E-01   0.000000000E+00
    14   0.164764459E-07   0.000000000E+00  -0.104095712E-01   0.000000000E+00  -0.252423144E-01   0.000000000E+00
    15   0.164762429E-07   0.000000000E+00  -0.474037818E-02   0.000000000E+00  -0.252426472E-01   0.000000000E+00
    16   0.164762467E-07   0.000000000E+00   0.928888684E-03   0.000000000E+00  -0.252429085E-01   0.000000000E+00
    17   0.164764318E-07   0.000000000E+00   0.659820563E-02   0.000000000E+00  -0.252431427E-01   0.000000000E+00
    18   0.164765001E-07   0.000000000E+00   0.122675886E-01   0.000000000E+00  -0.252434223E-01   0.000000000E+00
    19   0.164767725E-07   0.000000000E+00   0.179370280E-01   0.000000000E+00  -0.252436324E-01   0.000000000E+00
    20   0.164769397E-07   0.000000000E+00   0.236064944E-01   0.000000000E+00  -0.252437320E-01   0.000000000E+00
$MODE        4
  0.39578528E+02    0.10000000E+01
     1  -0.196674606E-10   0.000000000E+00  -0.940948699E-01   0.000000000E+00  -0.832574359E-01   0.000000000E+00
     2  -0.196569404E-10   0.000000000E+00  -0.755528337E-01   0.000000000E+00  -0.811642040E-01   0.000000000E+00
     3  -0.196438776E-10   0.000000000E+00  -0.574820026E-01   0.000000000E+00  -0.793728618E-01   0.000000000E+00
     4  -0.196294909E-10   0.000000000E+00  -0.398514493E-01   0.000000000E+00  -0.773592962E-01   0.000000000E+00
     5  -0.196085515E-10   0.000000000E+00  -0.226957854E-01   0.000000000E+00  -0.752126464E-01   0.000000000E+00
     6  -0.195733115E-10   0.000000000E+00  -0.605072729E-02   0.000000000E+00  -0.728500250E-01   0.000000000E+00
     7  -0.195189745E-10   0.000000000E+00   0.999375657E-02   0.000000000E+00  -0.698762023E-01   0.000000000E+00
     8  -0.194310574E-10   0.000000000E+00   0.251667634E-01   0.000000000E+00  -0.650673511E-01   0.000000000E+00
     9  -0.192301126E-10   0.000000000E+00   0.385939436E-01   0.000000000E+00  -0.542486112E-01   0.000000000E+00
    10  -0.187527067E-10   0.000000000E+00   0.480692442E-01   0.000000000E+00  -0.298348384E-01   0.000000000E+00
    11  -0.177861315E-10   0.000000000E+00   0.497151583E-01   0.000000000E+00   0.152179565E-01   0.000000000E+00
    12  -0.170248216E-10   0.000000000E+00   0.427938434E-01   0.000000000E+00   0.460931255E-01   0.000000000E+00
    13  -0.164465489E-10   0.000000000E+00   0.302250297E-01   0.000000000E+00   0.654000418E-01   0.000000000E+00
    14  -0.159615643E-10   0.000000000E+00   0.140827433E-01   0.000000000E+00   0.779001962E-01   0.000000000E+00
    15  -0.154475418E-10   0.000000000E+00  -0.444011542E-02   0.000000000E+00   0.865950757E-01   0.000000000E+00
    16  -0.163457478E-10   0.000000000E+00  -0.246143926E-01   0.000000000E+00   0.926210651E-01   0.000000000E+00
    17  -0.171261139E-10   0.000000000E+00  -0.460640822E-01   0.000000000E+00   0.978749675E-01   0.000000000E+00
    18  -0.172077810E-10   0.000000000E+00  -0.688371904E-01   0.000000000E+00   0.104034124E+00   0.000000000E+00
    19  -0.181612898E-10   0.000000000E+00  -0.928766367E-01   0.000000000E+00   0.108844570E+00   0.000000000E+00
    20  -0.196211395E-10   0.000000000E+00  -0.117685609E+00   0.000000000E+00   0.111273269E+00   0.000000000E+00
$MODE        5
  0.12813527E+03    0.10000000E+01
     1  -0.907625115E-11   0.000000000E+00   0.968081569E-01   0.000000000E+00   0.154702951E+00   0.000000000E+00
     2  -0.902546662E-11   0.000000000E+00   0.637533673E-01   0.000000000E+00   0.132130422E+00   0.000000000E+00
     3  -0.896248902E-11   0.000000000E+00   0.356576338E-01   0.000000000E+00   0.114445856E+00   0.000000000E+00
     4  -0.889342793E-11   0.000000000E+00   0.117573540E-01   0.000000000E+00   0.961796104E-01   0.000000000E+00
     5  -0.879336765E-11   0.000000000E+00  -0.800905964E-02   0.000000000E+00   0.784696414E-01   0.000000000E+00
     6  -0.862584956E-11   0.000000000E+00  -0.237779420E-01   0.000000000E+00   0.611194221E-01   0.000000000E+00
     7  -0.836958113E-11   0.000000000E+00  -0.354428711E-01   0.000000000E+00   0.423344610E-01   0.000000000E+00
     8  -0.795937497E-11   0.000000000E+00  -0.421502193E-01   0.000000000E+00   0.174577267E-01   0.000000000E+00
     9  -0.703515013E-11   0.000000000E+00  -0.411588404E-01   0.000000000E+00  -0.248775430E-01   0.000000000E+00
    10  -0.489271123E-11   0.000000000E+00  -0.280802414E-01   0.000000000E+00  -0.862419990E-01   0.000000000E+00
    11  -0.763923281E-12   0.000000000E+00  -0.247116908E-02   0.000000000E+00  -0.129348192E+00   0.000000000E+00
    12   0.218468815E-11   0.000000000E+00   0.250173782E-01   0.000000000E+00  -0.106471342E+00   0.000000000E+00
    13   0.414824446E-11   0.000000000E+00   0.439779910E-01   0.000000000E+00  -0.574837101E-01   0.000000000E+00
    14   0.555510239E-11   0.000000000E+00   0.509400078E-01   0.000000000E+00  -0.250947652E-02   0.000000000E+00
    15   0.731153851E-11   0.000000000E+00   0.453378353E-01   0.000000000E+00   0.523596798E-01   0.000000000E+00
    16   0.785238307E-11   0.000000000E+00   0.278018923E-01   0.000000000E+00   0.102117540E+00   0.000000000E+00
    17   0.680811381E-11   0.000000000E+00  -0.152755457E-02   0.000000000E+00   0.155252362E+00   0.000000000E+00
    18   0.606017142E-11   0.000000000E+00  -0.455361758E-01   0.000000000E+00   0.227685935E+00   0.000000000E+00
    19   0.399300425E-11   0.000000000E+00  -0.105588135E+00   0.000000000E+00   0.292053314E+00   0.000000000E+00
    20   0.400560848E-11   0.000000000E+00  -0.176909860E+00   0.000000000E+00   0.330321022E+00   0.000000000E+00
$MODE        6
  0.14555613E+03    0.10000000E+01
     1   0.451430537E-01   0.000000000E+00   0.171072781E-10   0.000000000E+00   0.297528981E-10   0.000000000E+00
     2   0.448173724E-01   0.000000000E+00   0.108209352E-10   0.000000000E+00   0.245027895E-10   0.000000000E+00
     3   0.444136522E-01   0.000000000E+00   0.567243532E-11   0.000000000E+00   0.205285354E-10   0.000000000E+00
     4   0.439714936E-01   0.000000000E+00   0.145821895E-11   0.000000000E+00   0.165205034E-10   0.000000000E+00
     5   0.433317349E-01   0.000000000E+00  -0.184936250E-11   0.000000000E+00   0.126643738E-10   0.000000000E+00
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      6   0.422625703E-01   0.000000000E+00  -0.429691255E-11   0.000000000E+00   0.899235455E-11   0.000000000E+00
      7   0.406312203E-01   0.000000000E+00  -0.588341524E-11   0.000000000E+00   0.510569235E-11   0.000000000E+00
      8   0.380291022E-01   0.000000000E+00  -0.646906729E-11   0.000000000E+00   0.194212983E-12   0.000000000E+00
      9   0.321934718E-01   0.000000000E+00  -0.560822502E-11   0.000000000E+00  -0.748326601E-11   0.000000000E+00
     10   0.187755529E-01   0.000000000E+00  -0.270906965E-11   0.000000000E+00  -0.171380536E-10   0.000000000E+00
     11  -0.665706935E-02   0.000000000E+00   0.177167264E-11   0.000000000E+00  -0.202400097E-10   0.000000000E+00
     12  -0.241979568E-01   0.000000000E+00   0.560384421E-11   0.000000000E+00  -0.122958849E-10   0.000000000E+00
     13  -0.352853940E-01   0.000000000E+00   0.720589387E-11   0.000000000E+00  -0.123345619E-11   0.000000000E+00
     14  -0.426711595E-01   0.000000000E+00   0.628238916E-11   0.000000000E+00   0.966177707E-11   0.000000000E+00
     15  -0.480636256E-01   0.000000000E+00   0.327043821E-11   0.000000000E+00   0.157369928E-10   0.000000000E+00
     16  -0.520377694E-01   0.000000000E+00  -0.211675587E-12   0.000000000E+00   0.141509428E-10   0.000000000E+00
     17  -0.543863935E-01   0.000000000E+00  -0.300581664E-11   0.000000000E+00   0.125765849E-10   0.000000000E+00
     18  -0.559362173E-01   0.000000000E+00  -0.776624123E-11   0.000000000E+00   0.337369389E-10   0.000000000E+00
     19  -0.572642995E-01   0.000000000E+00  -0.223937838E-10   0.000000000E+00   0.884017371E-10   0.000000000E+00
     20  -0.575988237E-01   0.000000000E+00  -0.512510924E-10   0.000000000E+00   0.148533026E-09   0.000000000E+00
$MODE        7
  0.22156564E+03    0.10000000E+01
      1   0.105529715E-14   0.000000000E+00   0.144094958E+00   0.000000000E+00   0.352565888E+00   0.000000000E+00
      2   0.100825832E-14   0.000000000E+00   0.724331088E-01   0.000000000E+00   0.252107231E+00   0.000000000E+00
      3   0.987348019E-15   0.000000000E+00   0.222540393E-01   0.000000000E+00   0.181248553E+00   0.000000000E+00
      4   0.978906718E-15   0.000000000E+00  -0.118119057E-01   0.000000000E+00   0.115241909E+00   0.000000000E+00
      5   0.944105450E-15   0.000000000E+00  -0.316546124E-01   0.000000000E+00   0.582112286E-01   0.000000000E+00
      6   0.867099109E-15   0.000000000E+00  -0.393952927E-01   0.000000000E+00   0.968076160E-02   0.000000000E+00
      7   0.815321115E-15   0.000000000E+00  -0.365954005E-01   0.000000000E+00  -0.339828277E-01   0.000000000E+00
      8   0.673628673E-15   0.000000000E+00  -0.236894835E-01   0.000000000E+00  -0.783292633E-01   0.000000000E+00
      9   0.390123055E-15   0.000000000E+00   0.355444777E-04   0.000000000E+00  -0.125840845E+00   0.000000000E+00
     10  -0.210060355E-15   0.000000000E+00   0.310339712E-01   0.000000000E+00  -0.135780412E+00   0.000000000E+00
     11  -0.122642120E-14   0.000000000E+00   0.513290906E-01   0.000000000E+00  -0.291346465E-01   0.000000000E+00
     12  -0.185659297E-14   0.000000000E+00   0.457303381E-01   0.000000000E+00   0.787371921E-01   0.000000000E+00
     13  -0.214504745E-14   0.000000000E+00   0.213803976E-01   0.000000000E+00   0.130876959E+00   0.000000000E+00
     14  -0.203549769E-14   0.000000000E+00  -0.882217712E-02   0.000000000E+00   0.129969208E+00   0.000000000E+00
     15  -0.222338059E-12   0.000000000E+00  -0.340284099E-01   0.000000000E+00   0.881382271E-01   0.000000000E+00
     16   0.338429084E-12   0.000000000E+00  -0.463775385E-01   0.000000000E+00   0.191597160E-01   0.000000000E+00
     17   0.185986768E-11   0.000000000E+00  -0.388748241E-01   0.000000000E+00  -0.829358340E-01   0.000000000E+00
     18   0.332671874E-11   0.000000000E+00   0.969905202E-03   0.000000000E+00  -0.255608418E+00   0.000000000E+00
     19   0.583168591E-11   0.000000000E+00   0.831077422E-01   0.000000000E+00  -0.437127873E+00   0.000000000E+00
     20   0.552204634E-11   0.000000000E+00   0.200719362E+00   0.000000000E+00  -0.566947930E+00   0.000000000E+00
$MODE        8
  0.32437990E+03    0.10000000E+01
      1  -0.274452591E-11   0.000000000E+00   0.170489903E+00   0.000000000E+00   0.600580929E+00   0.000000000E+00
      2  -0.264617816E-11   0.000000000E+00   0.546787659E-01   0.000000000E+00   0.345813255E+00   0.000000000E+00
      3  -0.252697307E-11   0.000000000E+00  -0.839010176E-02   0.000000000E+00   0.189340616E+00   0.000000000E+00
      4  -0.239919124E-11   0.000000000E+00  -0.379375658E-01   0.000000000E+00   0.640941693E-01   0.000000000E+00
      5  -0.221871777E-11   0.000000000E+00  -0.424614541E-01   0.000000000E+00  -0.256415183E-01   0.000000000E+00
      6  -0.192680862E-11   0.000000000E+00  -0.299052979E-01   0.000000000E+00  -0.840567635E-01   0.000000000E+00
      7  -0.150246680E-11   0.000000000E+00  -0.685489228E-02   0.000000000E+00  -0.116824254E+00   0.000000000E+00
      8  -0.868040358E-12   0.000000000E+00   0.207385568E-01   0.000000000E+00  -0.122684350E+00   0.000000000E+00
      9   0.431218622E-12   0.000000000E+00   0.438667933E-01   0.000000000E+00  -0.756264803E-01   0.000000000E+00
     10   0.296161078E-11   0.000000000E+00   0.452087283E-01   0.000000000E+00   0.622317833E-01   0.000000000E+00
     11   0.619203075E-11   0.000000000E+00   0.120519714E-01   0.000000000E+00   0.199866715E+00   0.000000000E+00
     12   0.661352904E-11   0.000000000E+00  -0.293139741E-01   0.000000000E+00   0.139379474E+00   0.000000000E+00
     13   0.552616883E-11   0.000000000E+00  -0.468416274E-01   0.000000000E+00   0.632153351E-02   0.000000000E+00
     14   0.379564776E-11   0.000000000E+00  -0.349804918E-01   0.000000000E+00  -0.107935727E+00   0.000000000E+00
     15   0.138401288E-11   0.000000000E+00  -0.302604868E-02   0.000000000E+00  -0.164887165E+00   0.000000000E+00
     16  -0.151928966E-11   0.000000000E+00   0.336535070E-01   0.000000000E+00  -0.149298812E+00   0.000000000E+00
     17  -0.379103660E-11   0.000000000E+00   0.569688628E-01   0.000000000E+00  -0.510727269E-01   0.000000000E+00
     18  -0.603180998E-11   0.000000000E+00   0.388398153E-01   0.000000000E+00   0.201387571E+00   0.000000000E+00
     19  -0.890446773E-11   0.000000000E+00  -0.515167512E-01   0.000000000E+00   0.540890429E+00   0.000000000E+00
     20  -0.909177014E-11   0.000000000E+00  -0.218308118E+00   0.000000000E+00   0.843532877E+00   0.000000000E+00
$MODE        9
  0.37006768E+03    0.10000000E+01
      1   0.317735637E-01   0.000000000E+00   0.221003542E-10   0.000000000E+00   0.891505283E-10   0.000000000E+00
      2   0.302918333E-01   0.000000000E+00   0.530017290E-11   0.000000000E+00   0.461424932E-10   0.000000000E+00
      3   0.285109922E-01   0.000000000E+00  -0.273169516E-11   0.000000000E+00   0.214955162E-10   0.000000000E+00
      4   0.266179926E-01   0.000000000E+00  -0.564361684E-11   0.000000000E+00   0.331849635E-11   0.000000000E+00
      5   0.239693391E-01   0.000000000E+00  -0.508231692E-11   0.000000000E+00  -0.826121762E-11   0.000000000E+00
      6   0.197394300E-01   0.000000000E+00  -0.247991394E-11   0.000000000E+00  -0.143542954E-10   0.000000000E+00
      7   0.137088399E-01   0.000000000E+00   0.100357210E-11   0.000000000E+00  -0.159236328E-10   0.000000000E+00
      8   0.493006627E-02   0.000000000E+00   0.429628035E-11   0.000000000E+00  -0.126065806E-10   0.000000000E+00
      9  -0.123543351E-01   0.000000000E+00   0.582803388E-11   0.000000000E+00  -0.600062888E-12   0.000000000E+00
     10  -0.434962968E-01   0.000000000E+00   0.341260380E-11   0.000000000E+00   0.200483262E-10   0.000000000E+00
     11  -0.746613963E-01   0.000000000E+00  -0.245406606E-11   0.000000000E+00   0.254799325E-10   0.000000000E+00
     12  -0.674934639E-01   0.000000000E+00  -0.628904900E-11   0.000000000E+00   0.545211515E-11   0.000000000E+00
     13  -0.442414719E-01   0.000000000E+00  -0.532422023E-11   0.000000000E+00  -0.135358040E-10   0.000000000E+00
     14  -0.170334578E-01   0.000000000E+00  -0.126672077E-11   0.000000000E+00  -0.203549750E-10   0.000000000E+00
     15   0.107076965E-01   0.000000000E+00   0.286784457E-11   0.000000000E+00  -0.144729598E-10   0.000000000E+00
     16   0.363999161E-01   0.000000000E+00   0.452426992E-11   0.000000000E+00   0.898729746E-12   0.000000000E+00
     17   0.542222882E-01   0.000000000E+00   0.178216409E-11   0.000000000E+00   0.212085114E-10   0.000000000E+00
     18   0.671496092E-01   0.000000000E+00  -0.496150288E-11   0.000000000E+00   0.317103159E-10   0.000000000E+00
     19   0.790560605E-01   0.000000000E+00  -0.902175209E-11   0.000000000E+00   0.386288438E-11   0.000000000E+00
     20   0.821397348E-01   0.000000000E+00  -0.109410916E-11   0.000000000E+00  -0.548792730E-10   0.000000000E+00
$MODE       10
  0.45394492E+03    0.10000000E+01
      1   0.306839988E-11   0.000000000E+00  -0.177769261E+00   0.000000000E+00  -0.889759293E+00   0.000000000E+00
      2   0.285312586E-11   0.000000000E+00  -0.168866163E-01   0.000000000E+00  -0.369516074E+00   0.000000000E+00
      3   0.259918118E-11   0.000000000E+00   0.407000026E-01   0.000000000E+00  -0.108834632E+00   0.000000000E+00
      4   0.233420688E-11   0.000000000E+00   0.476818082E-01   0.000000000E+00   0.501964151E-01   0.000000000E+00
      5   0.197115731E-11   0.000000000E+00   0.274866983E-01   0.000000000E+00   0.123067335E+00   0.000000000E+00
      6   0.140794920E-11   0.000000000E+00  -0.224915930E-02   0.000000000E+00   0.132999361E+00   0.000000000E+00
      7   0.640215607E-12   0.000000000E+00  -0.288603924E-01   0.000000000E+00   0.966436029E-01   0.000000000E+00
      8  -0.408407031E-12   0.000000000E+00  -0.416770861E-01   0.000000000E+00   0.143773606E-01   0.000000000E+00
      9  -0.227912612E-11   0.000000000E+00  -0.277862092E-01   0.000000000E+00  -0.127927180E+00   0.000000000E+00
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   10  -0.498594270E-11   0.000000000E+00   0.170955196E-01   0.000000000E+00  -0.230068698E+00   0.000000000E+00
   11  -0.563071325E-11   0.000000000E+00   0.526619157E-01   0.000000000E+00  -0.352910307E-01   0.000000000E+00
   12  -0.277721210E-11   0.000000000E+00   0.358668932E-01   0.000000000E+00   0.171946570E+00   0.000000000E+00
   13   0.325002956E-12   0.000000000E+00  -0.858189396E-02   0.000000000E+00   0.191771938E+00   0.000000000E+00
   14   0.260980914E-11   0.000000000E+00  -0.404677356E-01   0.000000000E+00   0.717904155E-01   0.000000000E+00
   15   0.349405421E-11   0.000000000E+00  -0.382571294E-01   0.000000000E+00  -0.914575797E-01   0.000000000E+00
   16   0.388797339E-11   0.000000000E+00  -0.329032651E-02   0.000000000E+00  -0.202489911E+00   0.000000000E+00
   17   0.481930904E-11   0.000000000E+00   0.455931817E-01   0.000000000E+00  -0.205587429E+00   0.000000000E+00
   18   0.488319736E-11   0.000000000E+00   0.661636912E-01   0.000000000E+00   0.427611300E-01   0.000000000E+00
   19   0.439678713E-11   0.000000000E+00  -0.112608933E-01   0.000000000E+00   0.576830200E+00   0.000000000E+00
   20   0.411328889E-11   0.000000000E+00  -0.237253460E+00   0.000000000E+00   0.122096404E+01   0.000000000E+00
$MODE       11
  0.53349915E+03     0.10000000E+01
    1  -0.520987930E-01   0.000000000E+00  -0.717624578E-11   0.000000000E+00  -0.427623856E-10   0.000000000E+00
    2  -0.470494357E-01   0.000000000E+00   0.268427593E-12   0.000000000E+00  -0.138335596E-10   0.000000000E+00
    3  -0.412239337E-01   0.000000000E+00   0.210575458E-11   0.000000000E+00  -0.123724094E-11   0.000000000E+00
    4  -0.352739743E-01   0.000000000E+00   0.168186330E-11   0.000000000E+00   0.478409202E-11   0.000000000E+00
    5  -0.273221947E-01   0.000000000E+00   0.407360712E-12   0.000000000E+00   0.603236544E-11   0.000000000E+00
    6  -0.154114742E-01   0.000000000E+00  -0.816809439E-12   0.000000000E+00   0.442230375E-11   0.000000000E+00
    7  -0.581571644E-04   0.000000000E+00  -0.146843263E-11   0.000000000E+00   0.116881070E-11   0.000000000E+00
    8   0.192237676E-01   0.000000000E+00  -0.121940200E-11   0.000000000E+00  -0.323256721E-11   0.000000000E+00
    9   0.490069645E-01   0.000000000E+00   0.120748096E-12   0.000000000E+00  -0.776468237E-11   0.000000000E+00
   10   0.771073026E-01   0.000000000E+00   0.183667626E-11   0.000000000E+00  -0.570353425E-11   0.000000000E+00
   11   0.381197682E-01   0.000000000E+00   0.165354768E-11   0.000000000E+00   0.719571145E-11   0.000000000E+00
   12  -0.203233791E-01   0.000000000E+00  -0.446340291E-12   0.000000000E+00   0.925824642E-11   0.000000000E+00
   13  -0.491915537E-01   0.000000000E+00  -0.190938023E-11   0.000000000E+00   0.265663269E-11   0.000000000E+00
   14  -0.498990072E-01   0.000000000E+00  -0.175664917E-11   0.000000000E+00  -0.348692424E-11   0.000000000E+00
   15  -0.307837636E-01   0.000000000E+00  -0.525151547E-12   0.000000000E+00  -0.742674091E-11   0.000000000E+00
   16   0.513839656E-03   0.000000000E+00   0.128075586E-11   0.000000000E+00  -0.737346979E-11   0.000000000E+00
   17   0.295238227E-01   0.000000000E+00   0.213354145E-11   0.000000000E+00   0.582662825E-12   0.000000000E+00
   18   0.538264207E-01   0.000000000E+00  -0.307549983E-12   0.000000000E+00   0.190692553E-10   0.000000000E+00
   19   0.785773236E-01   0.000000000E+00  -0.648043904E-11   0.000000000E+00   0.295822210E-10   0.000000000E+00
   20   0.852269510E-01   0.000000000E+00  -0.106159918E-10   0.000000000E+00   0.128297674E-10   0.000000000E+00
$MODE       12
  0.59547469E+03     0.10000000E+01
    1   0.218712018E-12   0.000000000E+00  -0.178223671E+00   0.000000000E+00  -0.120264339E+01   0.000000000E+00
    2   0.192315334E-12   0.000000000E+00   0.246844734E-01   0.000000000E+00  -0.305127524E+00   0.000000000E+00
    3   0.162466513E-12   0.000000000E+00   0.572494700E-01   0.000000000E+00   0.395917729E-01   0.000000000E+00
    4   0.132555620E-12   0.000000000E+00   0.326940434E-01   0.000000000E+00   0.163598248E+00   0.000000000E+00
    5   0.934926522E-13   0.000000000E+00  -0.465121283E-02   0.000000000E+00   0.150479997E+00   0.000000000E+00
    6   0.368956526E-13   0.000000000E+00  -0.306658213E-01   0.000000000E+00   0.698535271E-01   0.000000000E+00
    7  -0.321556576E-13   0.000000000E+00  -0.347124026E-01   0.000000000E+00  -0.351050571E-01   0.000000000E+00
    8  -0.111449079E-12   0.000000000E+00  -0.140093081E-01   0.000000000E+00  -0.138343166E+00   0.000000000E+00
    9  -0.213934597E-12   0.000000000E+00   0.252841779E-01   0.000000000E+00  -0.181718215E+00   0.000000000E+00
   10  -0.246124043E-12   0.000000000E+00   0.493518835E-01   0.000000000E+00  -0.495737920E-02   0.000000000E+00
   11   0.500788439E-13   0.000000000E+00   0.129242551E-01   0.000000000E+00   0.265881828E+00   0.000000000E+00
   12   0.208491790E-12   0.000000000E+00  -0.384483544E-01   0.000000000E+00   0.126108986E+00   0.000000000E+00
   13   0.171458914E-12   0.000000000E+00  -0.402267525E-01   0.000000000E+00  -0.112594255E+00   0.000000000E+00
   14   0.495388250E-13   0.000000000E+00  -0.112021232E-02   0.000000000E+00  -0.202719195E+00   0.000000000E+00
   15  -0.158618655E-12   0.000000000E+00   0.366635157E-01   0.000000000E+00  -0.103181285E+00   0.000000000E+00
   16  -0.155860286E-11   0.000000000E+00   0.379202394E-01   0.000000000E+00   0.938637631E-01   0.000000000E+00
   17  -0.402682046E-11   0.000000000E+00  -0.748981508E-02   0.000000000E+00   0.272493862E+00   0.000000000E+00
   18  -0.562766128E-11   0.000000000E+00  -0.684391488E-01   0.000000000E+00   0.192271767E+00   0.000000000E+00
   19  -0.669693418E-11   0.000000000E+00  -0.322020555E-01   0.000000000E+00  -0.490958021E+00   0.000000000E+00
   20  -0.668051788E-11   0.000000000E+00   0.259764053E+00   0.000000000E+00  -0.170453825E+01   0.000000000E+00
$MODE       13
  0.66563269E+03     0.10000000E+01
    1  -0.598871174E-01   0.000000000E+00   0.325063432E-11   0.000000000E+00   0.248494458E-10   0.000000000E+00
    2  -0.508517948E-01   0.000000000E+00  -0.806805706E-12   0.000000000E+00   0.447729039E-11   0.000000000E+00
    3  -0.408944693E-01   0.000000000E+00  -0.107337265E-11   0.000000000E+00  -0.227408106E-11   0.000000000E+00
    4  -0.311759842E-01   0.000000000E+00  -0.345763140E-12   0.000000000E+00  -0.370211709E-11   0.000000000E+00
    5  -0.188684246E-01   0.000000000E+00   0.376325134E-12   0.000000000E+00  -0.233332761E-11   0.000000000E+00
    6  -0.182756833E-02   0.000000000E+00   0.666308826E-12   0.000000000E+00  -0.108354547E-12   0.000000000E+00
    7   0.173802587E-01   0.000000000E+00   0.445140041E-12   0.000000000E+00   0.196393178E-11   0.000000000E+00
    8   0.365296267E-01   0.000000000E+00  -0.166526807E-12   0.000000000E+00   0.313330280E-11   0.000000000E+00
    9   0.534611827E-01   0.000000000E+00  -0.785764187E-12   0.000000000E+00   0.185192766E-11   0.000000000E+00
   10   0.329297519E-01   0.000000000E+00  -0.616884416E-12   0.000000000E+00  -0.313512125E-11   0.000000000E+00
   11  -0.626062167E-01   0.000000000E+00   0.465776331E-12   0.000000000E+00  -0.434018273E-11   0.000000000E+00
   12  -0.509136270E-01   0.000000000E+00   0.884792383E-12   0.000000000E+00   0.120668784E-11   0.000000000E+00
   13   0.183053797E-02   0.000000000E+00   0.228443197E-12   0.000000000E+00   0.379522872E-11   0.000000000E+00
   14   0.411837514E-01   0.000000000E+00  -0.438849308E-12   0.000000000E+00   0.126986168E-11   0.000000000E+00
   15   0.512379403E-01   0.000000000E+00  -0.452221602E-12   0.000000000E+00  -0.306167175E-13   0.000000000E+00
   16   0.297080371E-01   0.000000000E+00  -0.617265464E-12   0.000000000E+00   0.125589293E-11   0.000000000E+00
   17  -0.658405777E-02   0.000000000E+00  -0.776625335E-12   0.000000000E+00  -0.806311182E-12   0.000000000E+00
   18  -0.437091415E-01   0.000000000E+00   0.719711117E-12   0.000000000E+00  -0.124193987E-10   0.000000000E+00
   19  -0.863757044E-01   0.000000000E+00   0.499024591E-11   0.000000000E+00  -0.185246592E-10   0.000000000E+00
   20  -0.983169796E-01   0.000000000E+00   0.465124614E-11   0.000000000E+00   0.115265702E-10   0.000000000E+00
$MODE       14
  0.73973021E+03     0.10000000E+01
    1   0.623401668E-12   0.000000000E+00   0.164577292E+00   0.000000000E+00   0.142421921E+01   0.000000000E+00
    2   0.507233060E-12   0.000000000E+00  -0.595328874E-01   0.000000000E+00   0.145208740E+00   0.000000000E+00
    3   0.383134119E-12   0.000000000E+00  -0.516053639E-01   0.000000000E+00  -0.202978188E+00   0.000000000E+00
    4   0.265812957E-12   0.000000000E+00  -0.966555370E-03   0.000000000E+00  -0.207334911E+00   0.000000000E+00
    5   0.122829983E-12   0.000000000E+00   0.333090928E-01   0.000000000E+00  -0.752565081E-01   0.000000000E+00
    6  -0.637992816E-13   0.000000000E+00   0.345619965E-01   0.000000000E+00   0.657758413E-01   0.000000000E+00
    7  -0.252057428E-12   0.000000000E+00   0.839109571E-02   0.000000000E+00   0.153615086E+00   0.000000000E+00
    8  -0.399537675E-12   0.000000000E+00  -0.277984675E-01   0.000000000E+00   0.146910241E+00   0.000000000E+00
    9  -0.419344359E-12   0.000000000E+00  -0.427184099E-01   0.000000000E+00  -0.266811368E-01   0.000000000E+00
   10   0.720323078E-13   0.000000000E+00  -0.203744862E-02   0.000000000E+00  -0.275253366E+00   0.000000000E+00
   11   0.784909708E-12   0.000000000E+00   0.475775318E-01   0.000000000E+00  -0.522492914E-01   0.000000000E+00
   12   0.631339152E-13   0.000000000E+00   0.228672363E-01   0.000000000E+00   0.235059036E+00   0.000000000E+00
   13  -0.503440936E-12   0.000000000E+00  -0.289238623E-01   0.000000000E+00   0.161189857E+00   0.000000000E+00
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    14  -0.516379796E-12   0.000000000E+00  -0.393486823E-01   0.000000000E+00  -0.797856801E-01   0.000000000E+00
    15  -0.745226224E-12   0.000000000E+00  -0.191635831E-02   0.000000000E+00  -0.216358182E+00   0.000000000E+00
    16  -0.158749913E-11   0.000000000E+00   0.406007987E-01   0.000000000E+00  -0.122715154E+00   0.000000000E+00
    17  -0.222856100E-11   0.000000000E+00   0.360176800E-01   0.000000000E+00   0.153346499E+00   0.000000000E+00
    18  -0.216965467E-11   0.000000000E+00  -0.376722469E-01   0.000000000E+00   0.385209535E+00   0.000000000E+00
    19  -0.966811998E-12   0.000000000E+00  -0.683162434E-01   0.000000000E+00  -0.215492605E+00   0.000000000E+00
    20  -0.885400042E-12   0.000000000E+00   0.250686029E+00   0.000000000E+00  -0.202285634E+01   0.000000000E+00
$MODE       15
  0.80825867E+03    0.10000000E+01
     1  -0.715220944E-01   0.000000000E+00  -0.203287182E-11   0.000000000E+00  -0.195501042E-10   0.000000000E+00
     2  -0.556116635E-01   0.000000000E+00   0.943692989E-12   0.000000000E+00  -0.673811517E-12   0.000000000E+00
     3  -0.391683053E-01   0.000000000E+00   0.568648917E-12   0.000000000E+00   0.349558960E-11   0.000000000E+00
     4  -0.241300421E-01   0.000000000E+00  -0.188989158E-12   0.000000000E+00   0.259059524E-11   0.000000000E+00
     5  -0.656240701E-02   0.000000000E+00  -0.530050051E-12   0.000000000E+00   0.201623777E-12   0.000000000E+00
     6   0.148617360E-01   0.000000000E+00  -0.356735893E-12   0.000000000E+00  -0.165213863E-11   0.000000000E+00
     7   0.335969301E-01   0.000000000E+00   0.116883910E-12   0.000000000E+00  -0.229519899E-11   0.000000000E+00
     8   0.429760429E-01   0.000000000E+00   0.540183612E-12   0.000000000E+00  -0.120196258E-11   0.000000000E+00
     9   0.275680182E-01   0.000000000E+00   0.434800159E-12   0.000000000E+00   0.202028472E-11   0.000000000E+00
    10  -0.454121438E-01   0.000000000E+00  -0.367643493E-12   0.000000000E+00   0.382239253E-11   0.000000000E+00
    11  -0.548368695E-01   0.000000000E+00  -0.647957217E-12   0.000000000E+00  -0.208227143E-11   0.000000000E+00
    12   0.406625591E-01   0.000000000E+00   0.157960394E-12   0.000000000E+00  -0.368777457E-11   0.000000000E+00
    13   0.539444140E-01   0.000000000E+00   0.650783894E-12   0.000000000E+00  -0.668956012E-13   0.000000000E+00
    14   0.100174861E-01   0.000000000E+00   0.345962473E-12   0.000000000E+00   0.209784213E-11   0.000000000E+00
    15  -0.386338661E-01   0.000000000E+00   0.127602826E-12   0.000000000E+00  -0.132526649E-11   0.000000000E+00
    16  -0.521594097E-01   0.000000000E+00   0.966321412E-12   0.000000000E+00  -0.506979531E-11   0.000000000E+00
    17  -0.228054840E-01   0.000000000E+00   0.183423832E-11   0.000000000E+00  -0.104623117E-11   0.000000000E+00
    18   0.224958651E-01   0.000000000E+00  -0.789321163E-13   0.000000000E+00   0.170679651E-10   0.000000000E+00
    19   0.853075621E-01   0.000000000E+00  -0.511639509E-11   0.000000000E+00   0.149864981E-10   0.000000000E+00
    20   0.103917364E+00   0.000000000E+00   0.355462486E-11   0.000000000E+00  -0.654069940E-10   0.000000000E+00
$MODE       16
  0.90414831E+03    0.10000000E+01
     1  -0.332944307E-10   0.000000000E+00   0.125334885E+00   0.000000000E+00   0.137791649E+01   0.000000000E+00
     2  -0.240262867E-10   0.000000000E+00  -0.751856645E-01   0.000000000E+00  -0.772672124E-01   0.000000000E+00
     3  -0.149440037E-10   0.000000000E+00  -0.247078657E-01   0.000000000E+00  -0.299777496E+00   0.000000000E+00
     4  -0.708482188E-11   0.000000000E+00   0.305297149E-01   0.000000000E+00  -0.137255026E+00   0.000000000E+00
     5   0.145218351E-11   0.000000000E+00   0.394298929E-01   0.000000000E+00   0.663402445E-01   0.000000000E+00
     6   0.106229116E-10   0.000000000E+00   0.112463986E-01   0.000000000E+00   0.166051094E+00   0.000000000E+00
     7   0.163575296E-10   0.000000000E+00  -0.250646439E-01   0.000000000E+00   0.133547977E+00   0.000000000E+00
     8   0.149425062E-10   0.000000000E+00  -0.385109017E-01   0.000000000E+00  -0.226453139E-01   0.000000000E+00
     9  -0.208459461E-11   0.000000000E+00  -0.418034624E-02   0.000000000E+00  -0.241008580E+00   0.000000000E+00
    10  -0.326763381E-10   0.000000000E+00   0.489559192E-01   0.000000000E+00  -0.134165841E+00   0.000000000E+00
    11   0.211887308E-10   0.000000000E+00   0.178658069E-01   0.000000000E+00   0.327640327E+00   0.000000000E+00
    12   0.980059780E-11   0.000000000E+00  -0.444205781E-01   0.000000000E+00   0.102133020E+00   0.000000000E+00
    13  -0.139245277E-10   0.000000000E+00  -0.271860198E-01   0.000000000E+00  -0.227653646E+00   0.000000000E+00
    14  -0.146958078E-10   0.000000000E+00   0.282008192E-01   0.000000000E+00  -0.189976249E+00   0.000000000E+00
    15   0.178835967E-11   0.000000000E+00   0.402077470E-01   0.000000000E+00   0.100347843E+00   0.000000000E+00
    16   0.163109447E-10   0.000000000E+00  -0.837042620E-02   0.000000000E+00   0.276936692E+00   0.000000000E+00
    17   0.129854541E-10   0.000000000E+00  -0.590080070E-01   0.000000000E+00   0.114842015E+00   0.000000000E+00
    18   0.147995331E-12   0.000000000E+00  -0.136596665E-01   0.000000000E+00  -0.430978297E+00   0.000000000E+00
    19  -0.229438739E-10   0.000000000E+00   0.902409263E-01   0.000000000E+00  -0.186169207E+00   0.000000000E+00
    20  -0.293099927E-10   0.000000000E+00  -0.215538698E+00   0.000000000E+00   0.213539382E+01   0.000000000E+00
$MODE       17
  0.90787455E+03    0.10000000E+01
     1  -0.839427312E-01   0.000000000E+00  -0.487014235E-10   0.000000000E+00  -0.538048128E-09   0.000000000E+00
     2  -0.603827062E-01   0.000000000E+00   0.294652998E-10   0.000000000E+00   0.319860534E-10   0.000000000E+00
     3  -0.373469083E-01   0.000000000E+00   0.941265880E-11   0.000000000E+00   0.117703360E-09   0.000000000E+00
     4  -0.174605900E-01   0.000000000E+00  -0.121466584E-10   0.000000000E+00   0.527814891E-10   0.000000000E+00
     5   0.407151877E-02   0.000000000E+00  -0.153762259E-10   0.000000000E+00  -0.271013874E-10   0.000000000E+00
     6   0.270648429E-01   0.000000000E+00  -0.415730028E-11   0.000000000E+00  -0.653667577E-10   0.000000000E+00
     7   0.411731231E-01   0.000000000E+00   0.100020659E-10   0.000000000E+00  -0.514371128E-10   0.000000000E+00
     8   0.370229784E-01   0.000000000E+00   0.149561566E-10   0.000000000E+00   0.105479229E-10   0.000000000E+00
     9  -0.666907253E-02   0.000000000E+00   0.120607713E-11   0.000000000E+00   0.949928022E-10   0.000000000E+00
    10  -0.825642535E-01   0.000000000E+00  -0.192917000E-10   0.000000000E+00   0.495532968E-10   0.000000000E+00
    11   0.582848864E-01   0.000000000E+00  -0.642647038E-11   0.000000000E+00  -0.129319550E-09   0.000000000E+00
    12   0.206726952E-01   0.000000000E+00   0.176203169E-10   0.000000000E+00  -0.363410119E-10   0.000000000E+00
    13  -0.390250305E-01   0.000000000E+00   0.100602082E-10   0.000000000E+00   0.914963215E-10   0.000000000E+00
    14  -0.355515062E-01   0.000000000E+00  -0.117699431E-10   0.000000000E+00   0.734857253E-10   0.000000000E+00
    15   0.832947839E-02   0.000000000E+00  -0.161650620E-10   0.000000000E+00  -0.403681420E-10   0.000000000E+00
    16   0.426456286E-01   0.000000000E+00   0.288529800E-11   0.000000000E+00  -0.107700692E-09   0.000000000E+00
    17   0.313579682E-01   0.000000000E+00   0.224189865E-10   0.000000000E+00  -0.436450115E-10   0.000000000E+00
    18  -0.386646183E-02   0.000000000E+00   0.490568016E-11   0.000000000E+00   0.164188125E-09   0.000000000E+00
    19  -0.626188342E-01   0.000000000E+00  -0.335867572E-10   0.000000000E+00   0.637454968E-10   0.000000000E+00
    20  -0.808972379E-01   0.000000000E+00   0.843949901E-10   0.000000000E+00  -0.819875750E-09   0.000000000E+00
$MODE       18
  0.10390886E+04    0.10000000E+01
     1  -0.381985599E-01   0.000000000E+00   0.206093278E-11   0.000000000E+00   0.268169994E-10   0.000000000E+00
     2  -0.241544852E-01   0.000000000E+00  -0.161152125E-11   0.000000000E+00  -0.466944237E-11   0.000000000E+00
     3  -0.115928496E-01   0.000000000E+00  -0.587344645E-13   0.000000000E+00  -0.662633733E-11   0.000000000E+00
     4  -0.174435744E-02   0.000000000E+00   0.918430663E-12   0.000000000E+00  -0.960592167E-12   0.000000000E+00
     5   0.753874281E-02   0.000000000E+00   0.631698247E-12   0.000000000E+00   0.326165856E-11   0.000000000E+00
     6   0.149135160E-01   0.000000000E+00  -0.215683181E-12   0.000000000E+00   0.360252047E-11   0.000000000E+00
     7   0.149233153E-01   0.000000000E+00  -0.752101605E-12   0.000000000E+00   0.793126296E-12   0.000000000E+00
     8   0.455726230E-02   0.000000000E+00  -0.436520411E-12   0.000000000E+00  -0.327788358E-11   0.000000000E+00
     9  -0.207025921E-01   0.000000000E+00   0.621918407E-12   0.000000000E+00  -0.466472245E-11   0.000000000E+00
    10  -0.201563243E-01   0.000000000E+00   0.853956422E-12   0.000000000E+00   0.314067350E-11   0.000000000E+00
    11   0.689462681E-01   0.000000000E+00  -0.642683344E-12   0.000000000E+00   0.525152168E-11   0.000000000E+00
    12  -0.804541950E-01   0.000000000E+00  -0.747726558E-12   0.000000000E+00  -0.461205783E-11   0.000000000E+00
    13  -0.114965471E-01   0.000000000E+00   0.603157420E-12   0.000000000E+00  -0.513190701E-11   0.000000000E+00
    14   0.606565325E-01   0.000000000E+00   0.118607804E-11   0.000000000E+00   0.350004943E-13   0.000000000E+00
    15   0.345365473E-01   0.000000000E+00   0.757972175E-12   0.000000000E+00   0.321694225E-11   0.000000000E+00
    16  -0.434486336E-01   0.000000000E+00   0.375793938E-13   0.000000000E+00   0.244101256E-11   0.000000000E+00
    17  -0.584030717E-01   0.000000000E+00   0.337831592E-14   0.000000000E+00  -0.220428652E-11   0.000000000E+00
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      18  -0.189565641E-01   0.000000000E+00   0.107177610E-11   0.000000000E+00  -0.414191065E-11   0.000000000E+00
      19   0.757526774E-01   0.000000000E+00   0.387038388E-12   0.000000000E+00   0.823502993E-11   0.000000000E+00
      20   0.107599730E+00   0.000000000E+00  -0.335980676E-11   0.000000000E+00   0.209078366E-10   0.000000000E+00
$MODE        19
  0.11032624E+04    0.10000000E+01
       1   0.231211682E-12   0.000000000E+00   0.955760030E-01   0.000000000E+00   0.134573620E+01   0.000000000E+00
       2   0.135399733E-12   0.000000000E+00  -0.829591652E-01   0.000000000E+00  -0.306548544E+00   0.000000000E+00
       3   0.539950522E-13   0.000000000E+00   0.688180292E-02   0.000000000E+00  -0.337237007E+00   0.000000000E+00
       4  -0.629919366E-14   0.000000000E+00   0.506164822E-01   0.000000000E+00   0.974114842E-03   0.000000000E+00
       5  -0.580289599E-13   0.000000000E+00   0.253397063E-01   0.000000000E+00   0.199820841E+00   0.000000000E+00
       6  -0.895068062E-13   0.000000000E+00  -0.202311116E-01   0.000000000E+00   0.166256378E+00   0.000000000E+00
       7  -0.693306731E-13   0.000000000E+00  -0.389942460E-01   0.000000000E+00  -0.145004327E-01   0.000000000E+00
       8   0.104095474E-13   0.000000000E+00  -0.104605988E-01   0.000000000E+00  -0.210462537E+00   0.000000000E+00
       9   0.145254918E-12   0.000000000E+00   0.421222417E-01   0.000000000E+00  -0.179101250E+00   0.000000000E+00
      10   0.920426641E-14   0.000000000E+00   0.278094353E-01   0.000000000E+00   0.277772123E+00   0.000000000E+00
      11  -0.277893206E-12   0.000000000E+00  -0.480746086E-01   0.000000000E+00   0.129108787E+00   0.000000000E+00
      12   0.483905712E-12   0.000000000E+00  -0.183507940E-01   0.000000000E+00  -0.318504844E+00   0.000000000E+00
      13  -0.156943665E-12   0.000000000E+00   0.429295671E-01   0.000000000E+00  -0.105169157E+00   0.000000000E+00
      14  -0.356772071E-12   0.000000000E+00   0.239952885E-01   0.000000000E+00   0.240439694E+00   0.000000000E+00
      15   0.457798936E-12   0.000000000E+00  -0.336434941E-01   0.000000000E+00   0.178349585E+00   0.000000000E+00
      16   0.168264426E-11   0.000000000E+00  -0.339347162E-01   0.000000000E+00  -0.179859601E+00   0.000000000E+00
      17   0.144648389E-11   0.000000000E+00   0.397806947E-01   0.000000000E+00  -0.357390382E+00   0.000000000E+00
      18  -0.200890190E-12   0.000000000E+00   0.596419683E-01   0.000000000E+00   0.234987673E+00   0.000000000E+00
      19  -0.222667632E-11   0.000000000E+00  -0.844376389E-01   0.000000000E+00   0.546335919E+00   0.000000000E+00
      20  -0.312059235E-11   0.000000000E+00   0.147829284E+00   0.000000000E+00  -0.182451038E+01   0.000000000E+00
$MODE        20
  0.11652801E+04    0.10000000E+01
       1  -0.146457417E+00   0.000000000E+00  -0.624763938E-13   0.000000000E+00  -0.938426738E-12   0.000000000E+00
       2  -0.787380349E-01   0.000000000E+00   0.591268408E-13   0.000000000E+00   0.257904317E-12   0.000000000E+00
       3  -0.243096006E-01   0.000000000E+00  -0.111525907E-13   0.000000000E+00   0.238046205E-12   0.000000000E+00
       4   0.134127659E-01   0.000000000E+00  -0.380860091E-13   0.000000000E+00  -0.283874536E-13   0.000000000E+00
       5   0.422759773E-01   0.000000000E+00  -0.130277374E-13   0.000000000E+00  -0.166543964E-12   0.000000000E+00
       6   0.530324532E-01   0.000000000E+00   0.211087303E-13   0.000000000E+00  -0.106343014E-12   0.000000000E+00
       7   0.285583765E-01   0.000000000E+00   0.272411104E-13   0.000000000E+00   0.571505744E-13   0.000000000E+00
       8  -0.271388138E-01   0.000000000E+00  -0.190537348E-14   0.000000000E+00   0.175331166E-12   0.000000000E+00
       9  -0.884122641E-01   0.000000000E+00  -0.353360425E-13   0.000000000E+00   0.700803373E-13   0.000000000E+00
      10   0.654305809E-01   0.000000000E+00  -0.691537205E-14   0.000000000E+00  -0.250980406E-12   0.000000000E+00
      11  -0.212432452E-01   0.000000000E+00   0.375848807E-13   0.000000000E+00   0.312064551E-13   0.000000000E+00
      12  -0.141823831E-03   0.000000000E+00  -0.807011430E-14   0.000000000E+00   0.256806514E-12   0.000000000E+00
      13   0.147990499E-01   0.000000000E+00  -0.465389780E-13   0.000000000E+00   0.445513738E-13   0.000000000E+00
      14  -0.457838050E-02   0.000000000E+00  -0.490059475E-13   0.000000000E+00   0.787511121E-13   0.000000000E+00
      15  -0.133786661E-01   0.000000000E+00  -0.727860018E-13   0.000000000E+00   0.382708969E-14   0.000000000E+00
      16   0.309569574E-02   0.000000000E+00  -0.374566597E-13   0.000000000E+00  -0.249723139E-12   0.000000000E+00
      17   0.132833304E-01   0.000000000E+00  -0.480976695E-14   0.000000000E+00   0.669040944E-13   0.000000000E+00
      18   0.846620429E-02   0.000000000E+00  -0.137900314E-12   0.000000000E+00   0.851814958E-12   0.000000000E+00
      19  -0.139220296E-01   0.000000000E+00  -0.229202915E-12   0.000000000E+00  -0.462501861E-12   0.000000000E+00
      20  -0.221770246E-01   0.000000000E+00   0.641007742E-12   0.000000000E+00  -0.558205150E-11   0.000000000E+00
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Listing 8.8.5 trim_output.dat

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          TRIM ITERATION NUMBER :   1

          SUMMARY  OF  TOTAL  AERODYNAMIC   FORCES  AND  MOMENTS

          MEAN FLOW CONDITION :

          MACH NUMBER                            : 0.600000E+01
          ALTITUDE IN METERS                     : 0.217924E+05
          DYNAMIC PRESSURE IN N/M^2              : 0.954531E+05
          ANGLE OF ATTACK IN DEGREES             : -.100000E+01
          CONTROL SURFACE DEFLECTION IN DEGREES  : 0.773000E+01


          TRIM VARIABLE: ALPHA =-0.173572E+01(DEG), DELTA =-0.876495E+00(DEG)


          FINAL TRIM POSITION: ALPHA =-0.273572E+01(DEG), DELTA = 0.685351E+01(DEG)

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           AERODYNAMIC STABILITY DERIVATIVES OF FULL SPAN MODEL
           REFERENCE AREA =    1.777327      REFERENCE CHORD =     4.267200
           X-CG =     2.101018        Z-CG =    6.9082335E-02
           TOTAL WEIGHT =     3067.581      NEWTON
           X AERODYNAMIC CENTER FROM X = 0 :      1.712372

                          DRAG COEFFICIENT                LIFT COEFFICIENT                MOMENT COEFFICIENT

                          RIGID           ELASTIC         RIGID           ELASTIC         RIGID           ELASTIC

MEAN FLOW                 0.6251E-01      0.6251E-01      0.1051E+00      0.1051E+00      0.2168E-02      0.2212E-02

ALPHA(/RAD)               -.9175E+00      -.9175E+00      0.2211E+01      0.2211E+01      0.1007E+00      0.1015E+00
```

DELTA(/RAD)	0.5636E-03	0.5636E-03	0.1313E+00	0.1313E+00	-.5641E-01	-.5642E-01

TRIM ITERATION NUMBER : 2

SUMMARY OF TOTAL AERODYNAMIC FORCES AND MOMENTS

MEAN FLOW CONDITION :

```
MACH NUMBER                          : 0.600000E+01
ALTITUDE IN METERS                   : 0.217924E+05
DYNAMIC PRESSURE IN N/M^2            : 0.957254E+05
ANGLE OF ATTACK IN DEGREES           : -.273572E+01
CONTROL SURFACE DEFLECTION IN DEGREES : 0.685351E+01
```

TRIM VARIABLE: ALPHA =-0.251336E-01(DEG), DELTA = 0.300794E+01(DEG)

FINAL TRIM POSITION: ALPHA =-0.276085E+01(DEG), DELTA = 0.986144E+01(DEG)

```
AERODYNAMIC STABILITY DERIVATIVES OF FULL SPAN MODEL
REFERENCE AREA =    1.777042      REFERENCE CHORD =     4.267200
X-CG =     2.101018       Z-CG =   4.5984499E-02
TOTAL WEIGHT =     3067.581      NEWTON
X AERODYNAMIC CENTER FROM X = 0 :      1.867303
```

	DRAG COEFFICIENT		LIFT COEFFICIENT		MOMENT COEFFICIENT	
	RIGID	ELASTIC	RIGID	ELASTIC	RIGID	ELASTIC
MEAN FLOW	0.8570E-01	0.8570E-01	0.3100E-01	0.3100E-01	0.2562E-02	0.2588E-02
ALPHA(/RAD)	-.6475E+00	-.6475E+00	0.2289E+01	0.2289E+01	0.6268E-01	0.6324E-01
DELTA(/RAD)	0.5436E-03	0.5436E-03	0.1155E+00	0.1155E+00	-.4872E-01	-.4878E-01

TRIM ITERATION NUMBER : 3

SUMMARY OF TOTAL AERODYNAMIC FORCES AND MOMENTS

MEAN FLOW CONDITION :

```
MACH NUMBER                          : 0.600000E+01
ALTITUDE IN METERS                   : 0.217924E+05
DYNAMIC PRESSURE IN N/M^2            : 0.957290E+05
ANGLE OF ATTACK IN DEGREES           : -.276085E+01
CONTROL SURFACE DEFLECTION IN DEGREES : 0.986144E+01
```

TRIM VARIABLE: ALPHA =-0.103209E-02(DEG), DELTA =-0.730282E-01(DEG)

FINAL TRIM POSITION: ALPHA =-0.276188E+01(DEG), DELTA = 0.978841E+01(DEG)

```
AERODYNAMIC STABILITY DERIVATIVES OF FULL SPAN MODEL
REFERENCE AREA =    1.777043      REFERENCE CHORD =     4.267200
X-CG =     2.101018       Z-CG =   4.5638017E-02
TOTAL WEIGHT =     3067.581      NEWTON
X AERODYNAMIC CENTER FROM X = 0 :      1.872830
```

	DRAG COEFFICIENT		LIFT COEFFICIENT		MOMENT COEFFICIENT	
	RIGID	ELASTIC	RIGID	ELASTIC	RIGID	ELASTIC
MEAN FLOW	0.8601E-01	0.8601E-01	0.3628E-01	0.3628E-01	-.9227E-04	-.7041E-04
ALPHA(/RAD)	-.6479E+00	-.6479E+00	0.2288E+01	0.2288E+01	0.6116E-01	0.6182E-01
DELTA(/RAD)	0.5386E-03	0.5386E-03	0.1331E+00	0.1331E+00	-.5604E-01	-.5611E-01

TRIM ITERATION NUMBER : 4

SUMMARY OF TOTAL AERODYNAMIC FORCES AND MOMENTS

MEAN FLOW CONDITION :

```
MACH NUMBER                          : 0.600000E+01
ALTITUDE IN METERS                   : 0.217924E+05
DYNAMIC PRESSURE IN N/M^2            : 0.957292E+05
ANGLE OF ATTACK IN DEGREES           : -.276188E+01
CONTROL SURFACE DEFLECTION IN DEGREES : 0.978841E+01
```

TRIM VARIABLE: ALPHA =-0.492109E-05(DEG), DELTA =-0.670263E-03(DEG)

FINAL TRIM POSITION: ALPHA =-0.276189E+01(DEG), DELTA = 0.978774E+01(DEG)

AERODYNAMIC STABILITY DERIVATIVES OF FULL SPAN MODEL
REFERENCE AREA = 1.777044 REFERENCE CHORD = 4.267200
X-CG = 2.101018 Z-CG = 4.5623757E-02
TOTAL WEIGHT = 3067.581 NEWTON
X AERODYNAMIC CENTER FROM X = 0 : 1.876536

	DRAG COEFFICIENT		LIFT COEFFICIENT		MOMENT COEFFICIENT	
	RIGID	ELASTIC	RIGID	ELASTIC	RIGID	ELASTIC
MEAN FLOW	0.8602E-01	0.8602E-01	0.3607E-01	0.3607E-01	-.2328E-04	-.6489E-06
ALPHA(/RAD)	-.6500E+00	-.6500E+00	0.2289E+01	0.2289E+01	0.6021E-01	0.6085E-01
DELTA(/RAD)	0.5389E-03	0.5389E-03	0.1326E+00	0.1326E+00	-.5585E-01	-.5592E-01

TRIM ITERATION NUMBER : 5

SUMMARY OF TOTAL AERODYNAMIC FORCES AND MOMENTS

MEAN FLOW CONDITION :

MACH NUMBER : 0.600000E+01
ALTITUDE IN METERS : 0.217924E+05
DYNAMIC PRESSURE IN N/M^2 : 0.957292E+05
ANGLE OF ATTACK IN DEGREES : -.276189E+01
CONTROL SURFACE DEFLECTION IN DEGREES : 0.978774E+01

TRIM VARIABLE: ALPHA =-0.114166E-04(DEG), DELTA =-0.211050E-03(DEG)

FINAL TRIM POSITION: ALPHA =-0.276190E+01(DEG), DELTA = 0.978753E+01(DEG)

AERODYNAMIC STABILITY DERIVATIVES OF FULL SPAN MODEL
REFERENCE AREA = 1.777043 REFERENCE CHORD = 4.267200
X-CG = 2.101018 Z-CG = 4.5623671E-02
TOTAL WEIGHT = 3067.581 NEWTON
X AERODYNAMIC CENTER FROM X = 0 : 1.872191

	DRAG COEFFICIENT		LIFT COEFFICIENT		MOMENT COEFFICIENT	
	RIGID	ELASTIC	RIGID	ELASTIC	RIGID	ELASTIC
MEAN FLOW	0.8602E-01	0.8602E-01	0.3607E-01	0.3607E-01	-.2294E-04	-.1936E-06
ALPHA(/RAD)	-.6463E+00	-.6463E+00	0.2288E+01	0.2288E+01	0.6134E-01	0.6200E-01
DELTA(/RAD)	0.5389E-03	0.5389E-03	0.1326E+00	0.1326E+00	-.5585E-01	-.5592E-01

TRIM ITERATION NUMBER : 6

SUMMARY OF TOTAL AERODYNAMIC FORCES AND MOMENTS

MEAN FLOW CONDITION :

MACH NUMBER : 0.600000E+01
ALTITUDE IN METERS : 0.217924E+05
DYNAMIC PRESSURE IN N/M^2 : 0.957292E+05
ANGLE OF ATTACK IN DEGREES : -.276190E+01
CONTROL SURFACE DEFLECTION IN DEGREES : 0.978753E+01

TRIM VARIABLE: ALPHA = 0.133668E-04(DEG), DELTA = 0.216527E-02(DEG)

FINAL TRIM POSITION: ALPHA =-0.276189E+01(DEG), DELTA = 0.978970E+01(DEG)

AERODYNAMIC STABILITY DERIVATIVES OF FULL SPAN MODEL
REFERENCE AREA = 1.777043 REFERENCE CHORD = 4.267200
X-CG = 2.101018 Z-CG = 4.5623533E-02
TOTAL WEIGHT = 3067.581 NEWTON
X AERODYNAMIC CENTER FROM X = 0 : 1.874963

	DRAG COEFFICIENT		LIFT COEFFICIENT		MOMENT COEFFICIENT	
	RIGID	ELASTIC	RIGID	ELASTIC	RIGID	ELASTIC
MEAN FLOW	0.8602E-01	0.8602E-01	0.3606E-01	0.3606E-01	-.2090E-04	0.2099E-05
ALPHA(/RAD)	-.6480E+00	-.6480E+00	0.2289E+01	0.2289E+01	0.6063E-01	0.6129E-01

DELTA(/RAD)	0.5389E-03	0.5389E-03	0.1326E+00	0.1326E+00	-.5585E-01	-.5591E-01

TRIM ITERATION NUMBER : 7

SUMMARY OF TOTAL AERODYNAMIC FORCES AND MOMENTS

MEAN FLOW CONDITION :

```
MACH NUMBER                              : 0.600000E+01
ALTITUDE IN METERS                       : 0.217924E+05
DYNAMIC PRESSURE IN N/M^2                : 0.957291E+05
ANGLE OF ATTACK IN DEGREES               : -.276189E+01
CONTROL SURFACE DEFLECTION IN DEGREES    : 0.978970E+01
```

TRIM VARIABLE: ALPHA =-0.117856E-05(DEG), DELTA =-0.131141E-02(DEG)

FINAL TRIM POSITION: ALPHA =-0.276189E+01(DEG), DELTA = 0.978839E+01(DEG)

```
AERODYNAMIC STABILITY DERIVATIVES OF FULL SPAN MODEL
REFERENCE AREA =    1.777043      REFERENCE CHORD =    4.267200
X-CG =    2.101018      Z-CG =   4.5623720E-02
TOTAL WEIGHT =    3067.581      NEWTON
X AERODYNAMIC CENTER FROM X = 0 :    1.876671
```

	DRAG COEFFICIENT		LIFT COEFFICIENT		MOMENT COEFFICIENT	
	RIGID	ELASTIC	RIGID	ELASTIC	RIGID	ELASTIC
MEAN FLOW	0.8602E-01	0.8602E-01	0.3607E-01	0.3607E-01	-.2394E-04	-.1279E-05
ALPHA(/RAD)	-.6488E+00	-.6488E+00	0.2290E+01	0.2290E+01	0.6019E-01	0.6084E-01
DELTA(/RAD)	0.5389E-03	0.5389E-03	0.1326E+00	0.1326E+00	-.5585E-01	-.5592E-01

TRIM ITERATION NUMBER : 8

SUMMARY OF TOTAL AERODYNAMIC FORCES AND MOMENTS

MEAN FLOW CONDITION :

```
MACH NUMBER                              : 0.600000E+01
ALTITUDE IN METERS                       : 0.217924E+05
DYNAMIC PRESSURE IN N/M^2                : 0.957291E+05
ANGLE OF ATTACK IN DEGREES               : -.276189E+01
CONTROL SURFACE DEFLECTION IN DEGREES    : 0.978839E+01
```

TRIM VARIABLE: ALPHA = 0.205561E-05(DEG), DELTA =-0.156982E-03(DEG)

FINAL TRIM POSITION: ALPHA =-0.276189E+01(DEG), DELTA = 0.978823E+01(DEG)

```
AERODYNAMIC STABILITY DERIVATIVES OF FULL SPAN MODEL
REFERENCE AREA =    1.777043      REFERENCE CHORD =    4.267200
X-CG =    2.101018      Z-CG =   4.5623697E-02
TOTAL WEIGHT =    3067.581      NEWTON
X AERODYNAMIC CENTER FROM X = 0 :    1.872713
```

	DRAG COEFFICIENT		LIFT COEFFICIENT		MOMENT COEFFICIENT	
	RIGID	ELASTIC	RIGID	ELASTIC	RIGID	ELASTIC
MEAN FLOW	0.8602E-01	0.8602E-01	0.3607E-01	0.3607E-01	-.2268E-04	-.1554E-06
ALPHA(/RAD)	-.6471E+00	-.6471E+00	0.2288E+01	0.2288E+01	0.6120E-01	0.6184E-01
DELTA(/RAD)	0.5389E-03	0.5389E-03	0.1326E+00	0.1326E+00	-.5585E-01	-.5592E-01

TRIM ITERATION NUMBER : 9

SUMMARY OF TOTAL AERODYNAMIC FORCES AND MOMENTS

MEAN FLOW CONDITION :

```
MACH NUMBER                              : 0.600000E+01
ALTITUDE IN METERS                       : 0.217924E+05
DYNAMIC PRESSURE IN N/M^2                : 0.957291E+05
ANGLE OF ATTACK IN DEGREES               : -.276189E+01
CONTROL SURFACE DEFLECTION IN DEGREES    : 0.978823E+01
```

```
TRIM VARIABLE: ALPHA =-0.458873E-05(DEG), DELTA = 0.643405E-03(DEG)


FINAL TRIM POSITION: ALPHA =-0.276189E+01(DEG), DELTA = 0.978887E+01(DEG)

-----------------------------------------------------
 AERODYNAMIC STABILITY DERIVATIVES OF FULL SPAN MODEL
 REFERENCE AREA =     1.777044      REFERENCE CHORD =     4.267200
 X-CG =     2.101018      Z-CG =    4.5623727E-02
 TOTAL WEIGHT =     3067.581      NEWTON
 X AERODYNAMIC CENTER FROM X = 0 :     1.879049
```

	DRAG COEFFICIENT		LIFT COEFFICIENT		MOMENT COEFFICIENT	
	RIGID	ELASTIC	RIGID	ELASTIC	RIGID	ELASTIC
MEAN FLOW	0.8602E-01	0.8602E-01	0.3606E-01	0.3606E-01	-.2225E-04	0.6328E-06
ALPHA(/RAD)	-.6509E+00	-.6509E+00	0.2290E+01	0.2290E+01	0.5955E-01	0.6021E-01
DELTA(/RAD)	0.5390E-03	0.5390E-03	0.1326E+00	0.1326E+00	-.5586E-01	-.5592E-01

```
-----------------------------------------------------

TRIM ITERATION NUMBER :   10

SUMMARY  OF  TOTAL  AERODYNAMIC   FORCES  AND  MOMENTS

MEAN FLOW CONDITION :

MACH NUMBER                           : 0.600000E+01
ALTITUDE IN METERS                    : 0.217924E+05
DYNAMIC PRESSURE IN N/M^2             : 0.957290E+05
ANGLE OF ATTACK IN DEGREES            : -.276189E+01
CONTROL SURFACE DEFLECTION IN DEGREES : 0.978887E+01


TRIM VARIABLE: ALPHA =-0.460579E-05(DEG), DELTA = 0.175394E-04(DEG)


FINAL TRIM POSITION: ALPHA =-0.276190E+01(DEG), DELTA = 0.978889E+01(DEG)

-----------------------------------------------------
 AERODYNAMIC STABILITY DERIVATIVES OF FULL SPAN MODEL
 REFERENCE AREA =     1.777043      REFERENCE CHORD =     4.267200
 X-CG =     2.101018      Z-CG =    4.5623649E-02
 TOTAL WEIGHT =     3067.581      NEWTON
 X AERODYNAMIC CENTER FROM X = 0 :     1.881174
```

	DRAG COEFFICIENT		LIFT COEFFICIENT		MOMENT COEFFICIENT	
	RIGID	ELASTIC	RIGID	ELASTIC	RIGID	ELASTIC
MEAN FLOW	0.8602E-01	0.8602E-01	0.3607E-01	0.3607E-01	-.2267E-04	0.2191E-07
ALPHA(/RAD)	-.6530E+00	-.6530E+00	0.2290E+01	0.2290E+01	0.5900E-01	0.5965E-01
DELTA(/RAD)	0.5389E-03	0.5389E-03	0.1326E+00	0.1326E+00	-.5585E-01	-.5592E-01

```
-----------------------------------------------------

FINAL TRIM ANGLE OF ATTACK IN DEGREES = -0.276190E+01
FINAL TRIM DELTA IN DEGREES =  0.978889E+01

-----------------------------------------------------
```

Listing 8.8.6 Prep_ASE.dat

A Matrix:

	1	2	3	4	5	6	7	8	9	10
1	0.0000E+00	1.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
2	0.0000E+00	-2.6360E-02	0.0000E+00	1.8640E+02	-9.8067E+00	-2.5716E-02	-1.9144E+00	-1.7635E+00	9.7859E-08	1.0687E-07
3	0.0000E+00	0.0000E+00	0.0000E+00	-1.7774E+03	1.7774E+03	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
4	0.0000E+00	-6.2310E-06	0.0000E+00	-3.6294E-01	-1.9679E-08	1.0000E+00	3.3610E-13	4.1994E-13	-1.4502E-11	-4.2204E-11
5	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	1.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
6	0.0000E+00	-1.3736E-05	0.0000E+00	1.2359E+01	-5.1430E-07	5.5900E-03	5.5138E-03	-4.1750E-02	-1.9703E-07	-1.8099E-07
7	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	1.0000E+00	0.0000E+00
8	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	1.0000E+00
9	0.0000E+00	-1.0008E-01	0.0000E+00	-1.2905E+03	2.5811E+03	1.4637E-01	-1.5665E+03	1.2274E-08	-7.9438E-03	-2.1889E-05
10	0.0000E+00	-1.3380E-01	0.0000E+00	9.2146E+02	-1.8429E+03	1.7026E-01	-9.5752E-09	-1.6419E+04	2.3872E-05	-2.5652E-02

B matrix:

```
 0.000000E+00
-0.146517E+00
 0.000000E+00
-0.202872E-01
 0.000000E+00
```

```
 -0.111612E+02
  0.000000E+00
  0.000000E+00
 -0.895936E+03
 -0.828795E+03

Eigenvalues of A:

(0.0000000E+00,0.0000000E+00)
(0.0000000E+00,0.0000000E+00)
(-1.2833595E-02,128.1353)
(-1.2833595E-02,-128.1353)
(-4.0302277E-03,39.57858)
(-4.0302277E-03,-39.57858)
(3.342636,0.0000000E+00)
(-3.699774,0.0000000E+00)
(-2.2065708E-02,0.0000000E+00)
(-4.3724137E-03,0.0000000E+00)

Damping Ratio (Zeta) and Frequency (Omega)
Zeta : -1.0015659E-04 Omega :   20.38516      Hz
Zeta : -1.0182850E-04 Omega :   6.296593      Hz
Zeta :    1.000000     Omega :  0.5317830     Hz
Zeta :   -1.000000     Omega :  0.5886003     Hz
Zeta :   -1.000000     Omega :  3.5104537E-03 Hz
Zeta :   -1.000000     Omega :  6.9561129E-04 Hz

Output Prepared for Analytical Solution of Flight Dynamic Model
-------------------------

Mass (m) =                      625.6124
Velocity (U) =                  1777.383
Surface Area (S) =              1.777043
Dynamic Pressure (q) =          95729.13
Moment of Inertia (Iyy) =       3632.134
Reference Length (c) =          4.267200
Cd wrt u (Cdu) =               1.2826486E-04
Cm wrt u (Cmu) =              -3.8179856E-05
Cl wrt u (Clu) =               1.2870191E-04

Cd wrt q (Cdq) =               7.8784697E-02
Cm wrt q (Cmq) =               2.4510620E-02
Cl wrt q (Clq) =              -2.6101999E-02

Cd wrt alpha (Cd_alpha) =    -0.6494278
Cm wrt alpha (Cm_alpha) =     6.1838981E-02
Cl wrt alpha (Cl_alpha) =      2.286335

Coefficient of drag (Cd) =    8.6021081E-02
Coefficient of moment(Cm)=   -2.2896980E-05
Coefficient of lift (Cl) =    3.6066845E-02
```

8.9 Subsequent Design Cycles for Converged Configuration

The trim angle of attack obtained from the TRIM analysis may not agree with the initially guessed design angle of attack specified in the UCDA input file vehicle.inp with the parameter AOADES. In order to match these two angles of attack, it is required to perform multiple design cycles by repeating the entire cycle described in Sections 8.1 through 8.8. For each new design cycle, the parameter AOADES is updated by the trim angle of attack computed by the previous design cycle. This multiple design cycle process terminates when the variation between AOADES and trim angle of attack becomes small; leading to a converged configuration.

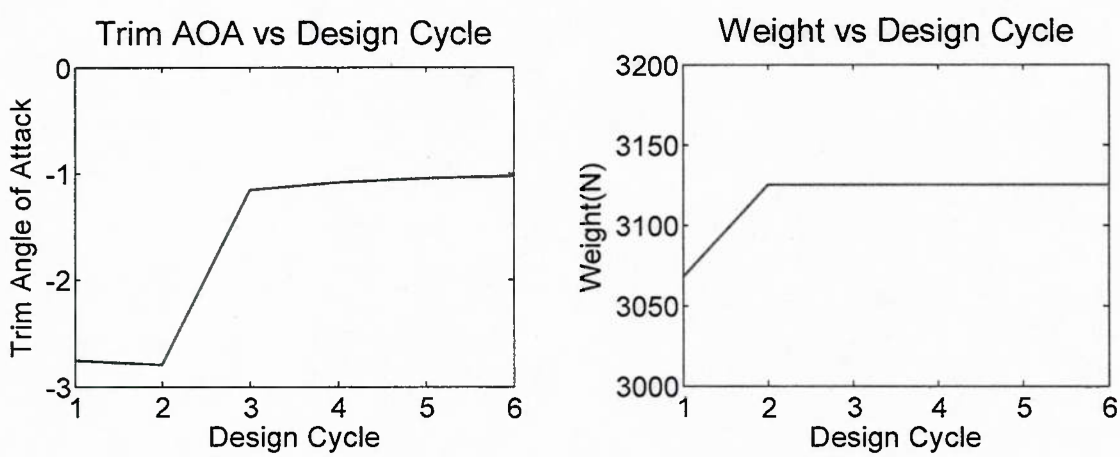


Figure 8.9.1 Convergence History of Angle of Attack and Weight for SEM Vehicle

For the present SEM configuration, it is found that this converged configuration is obtained after six design cycles. Figure 8.9.1 shows the trim angle of attack, control surface deflection angle and weight at each design cycle. It can be seen that at the sixth design cycle, the trim angle of attack is nearly converged at -1.029 degrees and the weight is nearly converged at 3125 Newton.

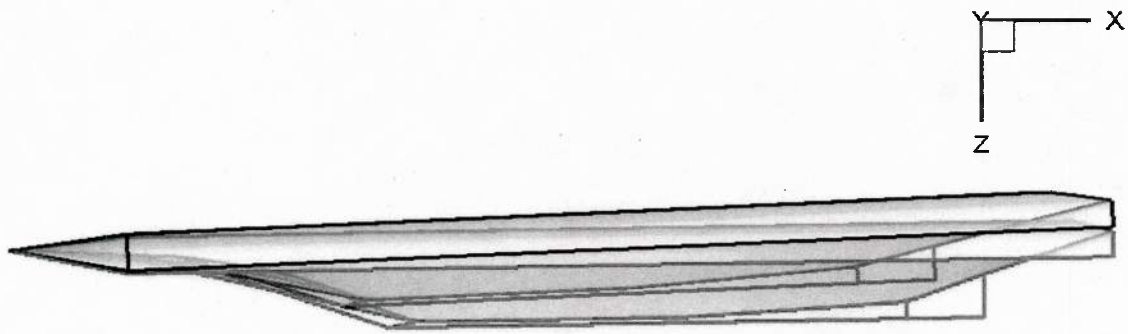


Figure. 8.9.2 Comparison of the SEM vehicle between first and final design cycles

Figure 8.9.2 shows the comparison of the vehicle geometry between first design cycle and the last design cycle. It can be seen that for the first design cycle, the vehicle had a higher negative trim angle of attack. That made the ramp angle narrower and thus in order to satisfy shock-on-lip condition, the inlet of the combustor was pushed forward by the design. On the other hand, for the final converged design, the trim angle of attack is smaller and thus the ramp angle is higher. Thus, to satisfy shock-on-lip condition, the inlet of the combustor is pushed backward.

The result of the SEM configuration suggests that this multiple design cycle process is a viable method to design such a vehicle even though there is not solid theoretical foundation to guarantee such a convergence at present.

Chapter 9 Case Study 2 - Single Engine Demo (SED)

9.1 Introduction

The second design study presented here is intended to "mimic" the Air Force's X-51 Single Engine Demo, as shown in Figure 9.1.1. The caveat here is that the entire geometry, including scramjet flowpath, fuel-injection arrangement, and booster integration have been assumed (or approximated) since no details have been provided. Furthermore, the internal layout and structural design have been neglected. The sample SED model is shown in Figure 9.1.2. While the basic design construct is similar to the SEM from Chapter 1, the upper surface of the vehicle (forebody and afterbody) have been generated using the Superformula of the Superellipse. While not a perfect match to the X-51 the process could be easily repeated with detail.

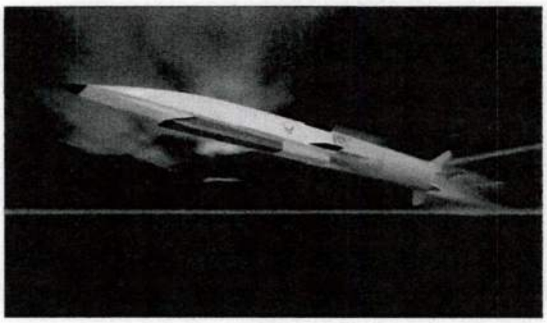


Figure 9.1.1 Air Force's X-51 Single Engine Demo (SED) vehicle.

Figure 9.1.2 Approximated Single Engine Demo (SED) vehicle.

9.2 Run UCDA to Design the Vehicle

Input Files:

File Name	Type	Remarks	See Listing
vehicle.inp	Standard input file	Also look at Table 9.2.1a and 9.2.1b	Shown in Listing 9.2.1
chem.bin	Engine chemistry information	Required	Shown in Listing 9.2.2
SEDvehicle.inp	Standard input file for SED type vehicle	Also look at Table 9.2.2	Shown in Listing 9.2.3

Output Files:

File Name	Type	Remarks	See Listing
plot.dat	Standard Tecplot output file	See Fig. 9.2.1	Shown in Listing 9.2.4

Input File descriptions

vehicle.inp: This is a standard input file for UCDA. See listing 9.2.1 for the entire input file. The part that is used to generate the geometry of the vehicle is shown in Tables 9.2.1a and 9.2.1b. Table 9.2.1a shows different patches that are needed to generate the vehicle. There are 21 patches in this SED vehicle. Each patch should have a name of the patch, the number of grids in the x direction and the number of grids in the y direction. Table 9.2.1b shows the other necessary geometrical and engine input parameters necessary to design the vehicle. The details of the definitions and explanations can be found in the User's Manual.

chem.bin: This is a required input file for the engine chemistry of the vehicle. Chem.bin is generated using ChemKin Version 2 and for this case is a Jet-A reaction mechanism. Please see Listing 9.2.2.

SEDvehicle.inp: This is a supplementary input file to generate the SED-like vehicle configuration. The parameters in this file override the geometry features from vehicle.inp for the vehicle upper surface using the Super Formula of the Super Ellipse for both the forebody and the afterbody mesh generation. The detail of SEDvehicle.inp is given in Section 3.3.2 of User's Manual. Please find SEDvehicle.inp in Listing 9.2.3.

Output File descriptions

plot.dat: The output file is a Tecplot format file that can easily be plotted. The plot of the designed vehicle is shown in Figure 9.2.1. This output file is shown in Listing 9.2.4.

The computational run time for UCDA to design a vehicle is about a few seconds.

Table 9.2.1a: Different Zones of SED Vehicle (see Figure 9.2.2; forebody top, keel top and atbody top not used by SED)

ZONE DATA AND GRID SIZES:			
21 NUMBER OF ZONES			
'forebody : top'	3	3	
'keel : top'	3	3	
'aftbody : top'	3	3	
'forebody : bot'	31	31	
'ramps : bot'	55	6	
'comb : bot'	101	6	
'cowl : top'	101	6	
'nozzle : bot'	31	6	
'ramp walls : inside'	35	6	
'comb wall : inside'	101	7	
'nozzle wall : inside'	21	7	
'aftbody : bot'	101	31	
'cowl : bot'	101	6	
'ramp walls : outside'	35	6	
'comb wall : outside'	101	7	
'nozzle wall : outside'	21	7	
'SEDbody : top'	121	46	
'Control_1 : top'	31	31	(Control surface dimensions must be the same)
'Control_1 : bottom'	31	31	(Control surface dimensions must be the same)
'Control_2 : top'	31	31	(Control surface dimensions must be the same)
'Control_2 : bottom'	31	31	(Control surface dimensions must be the same)

Table 9.2.1b: Geometrical and Engine Input Parameters of SED Vehicle

5.0	4	'Mdes'	- design Mach number
-1.2	0	'AOAdes'	- design angle of attack
26000.	1	'Zdes'	- design altitude
6.2672	1	'lvehicle'	- vehicle length
5.5939	0	'thforclu'	- forebody upper surface angle
3.8700	0	'thforcll'	- forebody ramp angle
0.5873	1	'lcontrol'	- control surface length
5.0	0	'th_control'	- control surface deflection angle
0.9920	0	'th_expn'	- nozzle initial expansion angle
10.8958	0	'th_exit'	- nozzle exit angle
0.0	4	'p_nozpoly'	- % diff between nozzle designs [DON'T USE-defaulted to 1.]
2.901	1	'lcowl'	- cowl length (isolator/combustor)
.3	1	'lcowlext'	- cowl extension length (internal nozzle)
0.545	4	'p_iso'	- percent of lcowl that is isolator
.3238	1	'height'	- height of vehicle (if required)

20.0	1	'linlet' - inlet length of vehicle (if required)
.28	1	'wengine' - width of the engine (currently defaulted to unit width)
3.00	4	'iramps' - number of inlet ramps in addition to the forebody
4.4615	0	'th_ramp1' - inlet ramp 1 angle
5.1567	0	'th_ramp2' - inlet ramp 2 angle
5.9844	0	'th_ramp3' - inlet ramp 3 angle
0.0	0	'th_ramp4' - inlet ramp 4 angle
0.0	0	'th_ramp5' - inlet ramp 5 angle
3.09	0	'th_div1' - first combustor expansion angle
1.2	0	'th_div2' - second combustor expansion angle
0.01	1	'Xinjs' - beginning of injectors (m)
0.02	1	'Xinje' - end of injectors (m)
0.01	1	'Lmix' - fuel mixing length (m)
1.00	4	'eta_mix' - fuel mixing and burning efficiency
4000.	4	'Tlimit' - maximum engine temperature (K)
90.	0	'Thetainj' - injector angle (degrees) [90 deg. is normal to flow]
1200.	4	'Tw' - adiabatic wall temperature (K)
0.1527	4	'nfor' - forebody exponent n
2.0	2	'wfor' - forebody width
2.0	1	'lfor' - forebody length
0.2427	4	'mfor' - forebody exponent m
5.797	0	'thforle' - forebody leading edge angle
21.519	0	'th_le' - leading edge attachment angle
0.0000	4	'p_kl' - keel-line height percentage
0.25	4	'fuelfrac' - vehicle fuel volume fraction
0.0104	2	't_plate' - shell plate thickness (Tungsten)
0.00000	4	'mass_smb' - mass due to Structural Modal Base (SMB) analysis
0.00000	4	'mass_tps' - mass due to Thermal Protection System (TPS) analysis
0.00000	4	'mass_nose' - mass due to Thermal Protection System (TPS) analysis

Table 9.2.2: SEDvehicle.inp

```
1    type of fit for upper profile (1=linear fit, 2=quadratic fit)
46   nphi - number of radial points [must be odd number]
2    number of cross sections input
read in cross section data (flag, naxi, n1, n2, n3, m, length, width, w/h ratio)
- lengths are sequential, widths are absolute, ratio is width/height
8 81 0.1 10. 10. 4.0 5.0 3.0 1.0
8 41 0.1 10. 10. 4.0 8.0 3.75 1.0
```

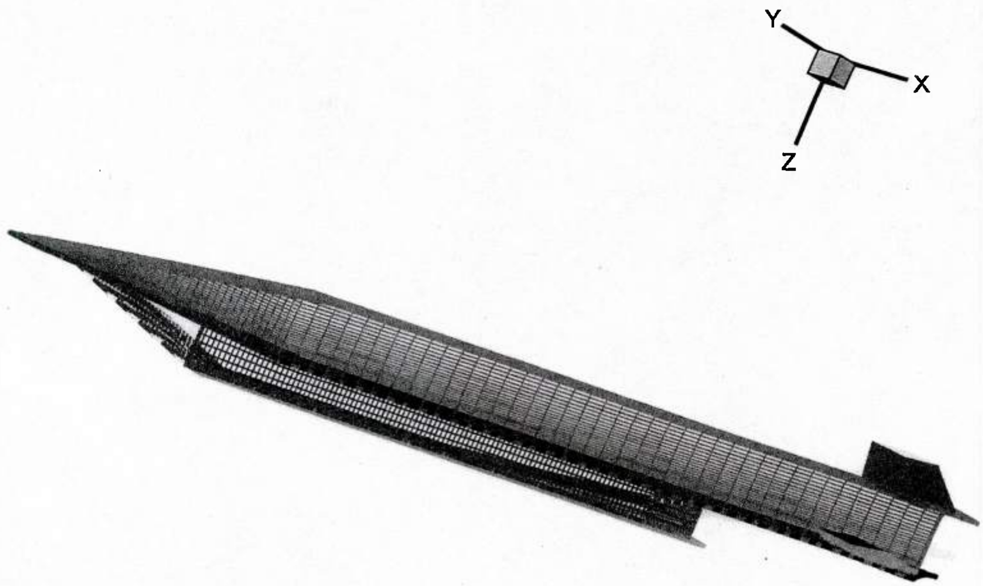
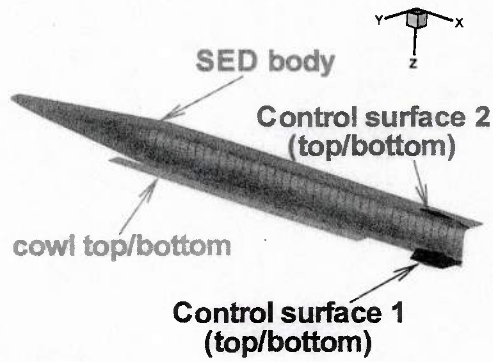
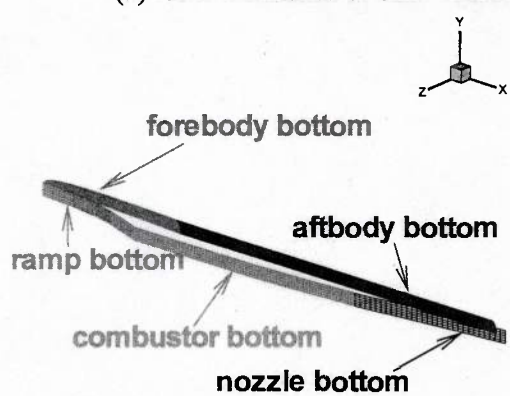


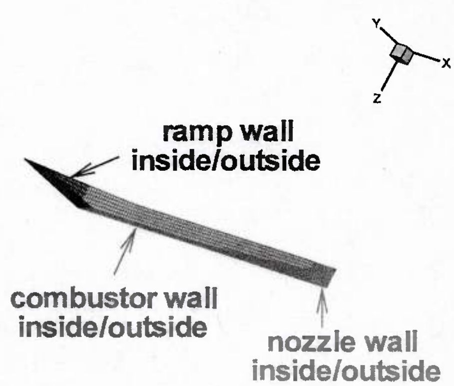
Figure 9.2.1 SED Vehicle Plot



(a) Selected Zones of SED Vehicle



(b) Selected Zones of SED Vehicle



(c) Selected Zones of SED Vehicle

Figure 9.2.2 Different Zones of SED Vehicle

Listing 9.2.1: Vehicle.inp Input File

```
TEST INPUT DECK:  Note - this line must be here!
2         ialtdyn - Inlet specified alt. (0), Fixed alt. (1), or Fixed dyn. press. (2)
1         ithrottle - Run engine as a function of: (0) equivalence ratio, (1) % throttle, (2) max throttle
1         iunits - Output unit switch: SI (1) or English (2)
3         ivisc - Viscous flag: inviscid (1), laminar (2), transitional (3), turbulent (4)
1         iequiv - find max equiv ratio for choked flow: off (0) -> single run, on (1)
2         inozorder - Nozzle polynomial order: 1st (flat plate) -> 3rd
1         iheight - Height constrained vehicle: no (0) = linlet set, yes (1) = height set
0         itrajectory - Run multiple trajectory points: no (0), discrete (1), matrix (2)
0         icone - cone flow data: exact (0), curve-fit approximation (1)
4         imodel - Forebody type: WA (1), VWA (2), VWA + cone flow (3), or SED (4)
0         itrim - Control surface deflection to trim the vehicle: no (0), yes (1), or optimize (2)
0         ideriv - Calculate derivatives: no (0), yes (1)
0         itps - If itps is 1, then prepare for tps and smb. ideriv and itps cannot be 1 at one time
1         ifeedback - If 1, then gets weight and Cg information from SMB and TPSOPT

OUTPUT FILE SWITCHES AND NAMES:
1   'plot.dat'                       VEHICLEFIG:          off (0), select (1), x,y,z (2), all (3)
3 1 2 3 8 18 23        1st # -> # of variables to read, others -> vars to plot
0   'metrics.dat'             METRICS:  off (0), on-real (1), on-cmplx (2)
0   'cowlexit.dat'            COWLEXIT:          off (0), on (1)
0   'moc.dat'                        NOZFIG:   off (0), P,T,M (1), all (2)
0   'offdesign.dat'                  AOA:                 off (0), on (1), UPTOP input tables (2), UPTOP input files (3)
0   'scramjet.dat'            CKENGINE: off (0), on (1)
0                                    IPRINTINLET:         off (0), all (1), results (2), all-real (3), results-real (4)
0                                    IPRINTENGINE:        off (0), on (1)
0                                    IDEBUG:            off (0), on (1) [print debugging info]

ZONE DATA AND GRID SIZES:
21        NUMBER OF ZONES
'forebody : top'          3        3
'keel : top'              3        3
'aftbody : top'           3        3
'forebody : bot'          31       31
'ramps : bot'             55       6
'comb : bot'              101      6
'cowl : top'              101      6
'nozzle : bot'            31       6
'ramp walls : inside'     35       6
'comb wall : inside'      101      7
'nozzle wall : inside'    21       7
'aftbody : bot'           101      31
'cowl : bot'              101      6
'ramp walls : outside'    35       6
'comb wall : outside'     101      7
'nozzle wall : outside'   21       7
'SEDbody : top'           121      46
'Control_1 : top'         31       31    (Control surface dimensions must be the same)
'Control_1 : bottom'      31       31    (Control surface dimensions must be the same)
'Control_2 : top'         31       31    (Control surface dimensions must be the same)
'Control_2 : bottom'      31       31    (Control surface dimensions must be the same)

INPUT DATA:  (0 = degrees, 1 = m, 2 = ft, 3 = atm, 4 = dimensionless, K or kg, 5 = psf)
Xl         x         xu         unit       res         name
22500.     26290.    30000.     1          2500.       'altitude' - altitude (if required)
1500.      1700.     2000.0     5           250.       'q0'       - dynamic pressure (if required)
.50        1.0299    1.0        4          .250        'equiv'    - equivalence ratio
1.          1.0      0.0        4          -.10        'throttle' - engine throttle (if required)
6.0        7.0       8.00       4            .5        'm0'       - Mach number
-2.00      0.0       3.00       0            .5        'AOA'      - angle of attack
5.0        4         'Mdes'       - design Mach number
0.2935     0         'AOAdes'     - design angle of attack
26000.     1         'Zdes'       - design altitude
6.2672     1         'lvehicle'   - vehicle length
5.5939     0         'thforclu'   - forebody upper surface angle
3.8700     0         'thforcll'   - forebody ramp angle
0.5873     1         'lcontrol'   - control surface length
5.0        0         'th_control'- control surface deflection angle
0.9920     0         'th_expn'    - nozzle initial expansion angle
10.8958    0         'th_exit'    - nozzle exit angle
0.0        4         'p_nozpoly' - % diff between nozzle designs [DON'T USE-defaulted to 1.]
2.901      1         'lcowl'      - cowl length (isolator/combustor)
.3         1         'lcowlext'  - cowl extension length (internal nozzle)
0.545      4         'p_iso'      - percent of lcowl that is isolator
.3238      1         'height'     - height of vehicle (if required)
20.0       1         'linlet'     - inlet length of vehicle (if required)
.28        1         'wengine'    - width of the engine (currently defaulted to unit width)
3.00       4         'iramps'     - number of inlet ramps in addition to the forebody
4.4615     0         'th_ramp1'   - inlet ramp 1 angle
5.1567     0         'th_ramp2'   - inlet ramp 2 angle
5.9844     0         'th_ramp3'   - inlet ramp 3 angle
0.0        0         'th_ramp4'   - inlet ramp 4 angle
0.0        0         'th_ramp5'   - inlet ramp 5 angle
3.09       0         'th_div1'    - first combustor expansion angle
1.2        0         'th_div2'    - second combustor expansion angle
0.01       1         'Xinjs'        - beginning of injectors (m)
0.02       1         'Xinje'      - end of injectors (m)
0.01       1         'Lmix'       - fuel mixing length (m)
1.00       4         'eta_mix'    - fuel mixing and burning efficiency
4000.      4         'Tlimit'     - maximum engine temperature (K)
90.        0         'Thetainj'   - injector angle (degrees) [90 deg. is normal to flow]
1200.      4         'Tw'         - adiabatic wall temperature (K)
```

```
0.1527     4        'nfor'       - forebody exponent n
2.0        2        'wfor'       - forebody width
2.0        1        'lfor'       - forebody length
0.2427     4        'mfor'       - forebody exponent m
5.797      0        'thforle'    - forebody leading edge angle
21.519     0        'th_le'      - leading edge attachment angle
0.0000     4        'p_kl'       - keel-line height percentage
0.25       4        'fuelfrac'   - vehicle fuel volume fraction
0.0104     2        't_plate'    - shell plate thickness (Tungsten)
0.00000    4        'mass_smb'   - mass due to Structural Modal Base (SMB) analysis
0.00000    4        'mass_tps'   - mass due to Thermal Protection System (TPS) analysis
0.00000    4        'mass_nose'  - mass due to Thermal Protection System (TPS) analysis
```

Listing 9.2.2: Chem.bin Input File

```
"3.6                " "DOUBLE          " .F.
 462 624 22 5 17 23 6 10 3 5 3 2 8 3 0 0 0 0 0 0 0 0 10  0.00100000005
 "H                 "  1.00796998
 "O                 "  15.9994001
 "C                 "  12.0111504
 "N                 "  14.0066996
 "AR                "  39.9480019
 "O2                " 0 2 0 0 0 0 0  31.9988003 3  300.  1000.  5000.  3.212936
  0.001127486 -5.75615E-07  1.313877E-09 -8.768554E-13 -1005.249  6.034738
  3.697578  0.0006135197 -1.258842E-07  1.775281E-11 -1.136435E-15 -1233.93
  3.189166
 "C12H23            " 23 0 12 0 0 0 0  167.317114 3  273.  1000.  5000.
  2.0869217  0.13314965 -8.1157452E-05  2.9409286E-08 -6.5195213E-12 -35912.814
  27.355289  24.880201  0.078250048 -3.1550973E-05  5.78789E-09 -3.9827968E-13
 -43110.684 -93.655255
 "H2                " 2 0 0 0 0 0 0  2.01593995 3  300.  1000.  5000.  3.298124
  0.0008249442 -8.143015E-07 -9.475434E-11  4.134872E-13 -1012.521 -3.294094
  2.991423  0.0007000644 -5.633829E-08 -9.231578E-12  1.582752E-15 -835.034
 -1.35511
 "H                 " 1 0 0 0 0 0 0  1.00796998 3  300.  1000.  5000.  2.5  0.
  0.  0.  0.  25471.63 -0.4601176  2.5  0.  0.  0.  0.  25471.63 -0.4601176
 "O                 " 0 1 0 0 0 0 0  15.9994001 3  300.  1000.  5000.  2.946429
 -0.001638166  2.421032E-06 -1.602843E-09  3.890696E-13  29147.64  2.963995
  2.54206 -2.755062E-05 -3.102803E-09  4.551067E-12 -4.368052E-16  29230.8
  4.920308
 "OH                " 1 1 0 0 0 0 0  17.0073701 3  300.  1000.  5000.  3.637266
  0.000185091 -1.676165E-06  2.387203E-09 -8.431442E-13  3606.782  1.35886
  2.88273  0.001013974 -2.276877E-07  2.174684E-11 -5.126305E-16  3886.888
  5.595712
 "HO2               " 1 2 0 0 0 0 0  33.0067703 3  300.  1000.  5000.  2.979963
  0.004996697 -3.790997E-06  2.354192E-09 -8.089024E-13  176.2274  9.222724
  4.072191  0.002131296 -5.308145E-07  6.112269E-11 -2.841165E-15 -157.9727
  3.476029
 "H2O               " 2 1 0 0 0 0 0  18.0153401 3  300.  1000.  5000.  3.386842
  0.003474982 -6.354696E-06  6.968581E-09 -2.506588E-12 -30208.11  2.590233
  2.672146  0.003056293 -8.73026E-07  1.200996E-10 -6.391618E-15 -29899.21
  6.862817
 "CH                " 1 0 1 0 0 0 0  13.0191203 3  300.  1000.  5000.  3.200202
  0.002072876 -5.134431E-06  5.73389E-09 -1.955533E-12  70452.59  3.331588
  2.196223  0.002340381 -7.058201E-07  9.007582E-11 -3.85504E-15  70867.23
  9.178373
 "CO2               " 0 2 1 0 0 0 0  44.0099506 3  300.  1000.  5000.  2.275725
  0.009922072 -1.040911E-05  6.866687E-09 -2.11728E-12 -48373.14  10.18849
  4.453623  0.003140169 -1.278411E-06  2.393997E-10 -1.669033E-14 -48966.96
 -0.9553959
 "CO                " 0 1 1 0 0 0 0  28.0105505 3  300.  1000.  5000.  3.262452
  0.001511941 -3.881755E-06  5.581944E-09 -2.474951E-12 -14310.54  4.848897
  3.025078  0.001442689 -5.630828E-07  1.018581E-10 -6.910952E-15 -14268.35
  6.108218
 "C2H2              " 2 0 2 0 0 0 0  26.0382407 3  300.  1000.  5000.  2.013562
  0.01519045 -1.616319E-05  9.078992E-09 -1.912746E-12  26124.44  8.805378
  4.43677  0.005376039 -1.912817E-06  3.286379E-10 -2.15671E-14  25667.66
 -2.800338
 "N                 " 0 0 0 1 0 0 0  14.0066996 3  300.  1000.  5000.  2.503071
 -2.180018E-05  5.420529E-08 -5.64756E-11  2.099904E-14  56098.9  4.167566
  2.450268  0.0001066146 -7.465337E-08  1.879652E-11 -1.025984E-15  56116.04
  4.448758
 "NH                " 1 0 0 1 0 0 0  15.0146695 3  300.  1000.  5000.  3.339758
  0.001253009 -3.491646E-06  4.218812E-09 -1.557618E-12  41850.47  2.507181
  2.760249  0.001375346 -4.451914E-07  7.692792E-11 -5.017592E-15  42078.28
  5.857199
 "NO                " 0 1 0 1 0 0 0  30.0060997 3  300.  1000.  5000.  3.376542
  0.001253063 -3.302751E-06  5.21781E-09 -2.446263E-12  9817.961  5.82959
  3.245435  0.001269138 -5.01589E-07  9.169283E-11 -6.275419E-15  9800.84
  6.417294
 "AR                " 0 0 0 0 1 0 0  39.9480019 3  300.  1000.  5000.  2.5  0.
  0.  0.  0. -745.375  4.366001  2.5  0.  0.  0.  0. -745.375  4.366001
 "N2                " 0 0 0 2 0 0 0  28.0133991 3  300.  1000.  5000.  3.298677
  0.00140824 -3.963222E-06  5.641515E-09 -2.444855E-12 -1020.9  3.950372
  2.92664  0.001487977 -5.684761E-07  1.009704E-10 -6.753351E-15 -922.7977
  5.980528
 -5 2  4.35E+09  0.  15098.1385 -1 2 -1 17 0 0 12 9 11 4 1 17 5 3  1.E+15  0.
  39255.16 -1 3 -1 17 -1 9 1 9 2 14 0 0 6 3  1.6E+09  0.5  22093.6093 -1 5 -1 17
 -1 7 2 15 1 4 1 5 4 2  3.E+13  1.  19124.3087 -1 3 -1 1 0 0 1 8 1 5 0 0 4 2
```

```
 2.5E+15  0.  3019.62769 -1 3 -1 5 0 0 1 4 1 6 0 0 4 2  4.E+14  0.  9058.88307
-1 4 -1 1 0 0 1 5 1 6 0 0 4 2  1.E+18  0.  61519.3782 -1 17 -1 1 0 0 2 5 1 17 0
0 3 2  4.E+20 -1.  0. -1 3 -2 4 0 0 2 3 0 0 0 0 3 2  1.E+15 -1.15  0. -1 4 -1 1
0 0 1 7 0 0 0 0 4 2  1.E+13  0.  0. -1 6 -1 7 0 0 1 8 1 1 0 0 4 2  6.5E+13  0.
 0. -1 4 -1 7 0 0 1 3 1 1 0 0 4 2  2.5E+13  0.  0. -1 5 -1 7 0 0 1 6 1 1 0 0 4
2  15100000.  1.28 -381.479632 -1 11 -1 6 0 0 1 10 1 4 0 0 4 2  1.5E+17  0.
-381.479632 -1 17 -2 9 0 0 1 12 1 17 0 0 4 2  3.E+15  0.  9562.15435 -1 12 -1 1
0 0 2 11 1 3 0 0 4 2  3.E+13  0.  3019.62769 -1 9 -1 6 0 0 1 11 1 3 0 0 4 2
 3.E+12  0.6  0. -1 9 -1 5 0 0 1 11 1 4 0 0 4 2  1.E+11  0.  0. -1 9 -1 15 0 0
1 14 1 11 0 0 4 2  9.E+13  0.  37745.3461 -1 17 -1 5 0 0 1 13 1 15 0 0 4 2
 6.3E+09  1.  3170.60907 -1 13 -1 1 0 0 1 15 1 5 0 0 4 2  1.E+12  0.
 24157.0215 -1 15 -1 4 0 0 1 13 1 6 0 0 4 2  25000.  2.64  0. -1 14 -1 5 0 0 1
15 1 4 0 0 4 2  2.E+15 -0.8  0. -1 14 -1 15 0 0 1 17 1 6 0 0
2  1.95E+15  0.  0. 3  2.5E+10  0.  4026.17025 7  4.E+18  0.  0.
```

Listing 9.2.3: SEDvehicle.inp Input File

```
1      type of fit for upper profile (1=linear fit, 2=quadratic fit)
46     nphi  - number of radial pointa [muat be odd number]
2      number of cross sections input
read in cross section data (flag, naxi, n1, n2, n3, m, length, width, w/h ratio)
- lengths are sequential, widths are abaolute, ratio is width/height
8  81  0.1   10.   10.   4.0   5.0   3.0   1.0
8  41  0.1   10.   10.   4.0   8.0   3.75  1.0
```

Listing 9.2.4: Plot.dat TECPLOT output file

```
variables =
 "x"
 "y"
 "z"
 "yz-area"
 "xz-area"
 "xy-area"
 "SA"
 "p"
 "T"
 "M"
 "viac-length"
 "Dv-l/area"
 "Dv-t/area"
 "ave-x"
 "ave-y"
 "ave-z"
 "yz-R-of-Curv"
 "gamma"
 "R"
 "x-norm-vec"
 "y-norm-vec"
 "z-norm-vec"
 "u-vel"
 "v-vel"
 "w-vel"
 "phi"
 "dphi"
 "x0"
 "y0"
 "z0"
 "r0"
 "th0"
 "qdot"
 "psf"
 ""
 zone f=block, t="forebody : bot            ",                    i=          31
 ,j=          31
  0.1999999762E+01
  0.1775430322E+01
  0.1572604299E+01
  0.1389763594E+01
  0.1225263357E+01
  0.1077568293E+01
  0.9452453256E+00
  0.8269558549E+00
  0.7214568257E+00
  0.6275903583E+00
  0.5442843437E+00
  0.4705444276E+00
  0.4054505527E+00
  0.3481531441E+00
  0.2978700101E+00
  0.2538813055E+00
  0.2155252993E+00
  0.1821971089E+00  .........
```

```
.........
.........
.........
0.0000000000E+00
0.0000000000E+00
0.0000000000E+00
0.0000000000E+00
0.0000000000E+00
0.0000000000E+00
0.0000000000E+00
0.0000000000E+00
0.0000000000E+00
0.0000000000E+00
0.0000000000E+00
0.0000000000E+00
```

9.3 Run UCDA to Generate Tables and Input Files for UPTOP

This section corresponds to the Step 1 in the Graphical User Interface (GUI). See Figure 9.3.1 below.

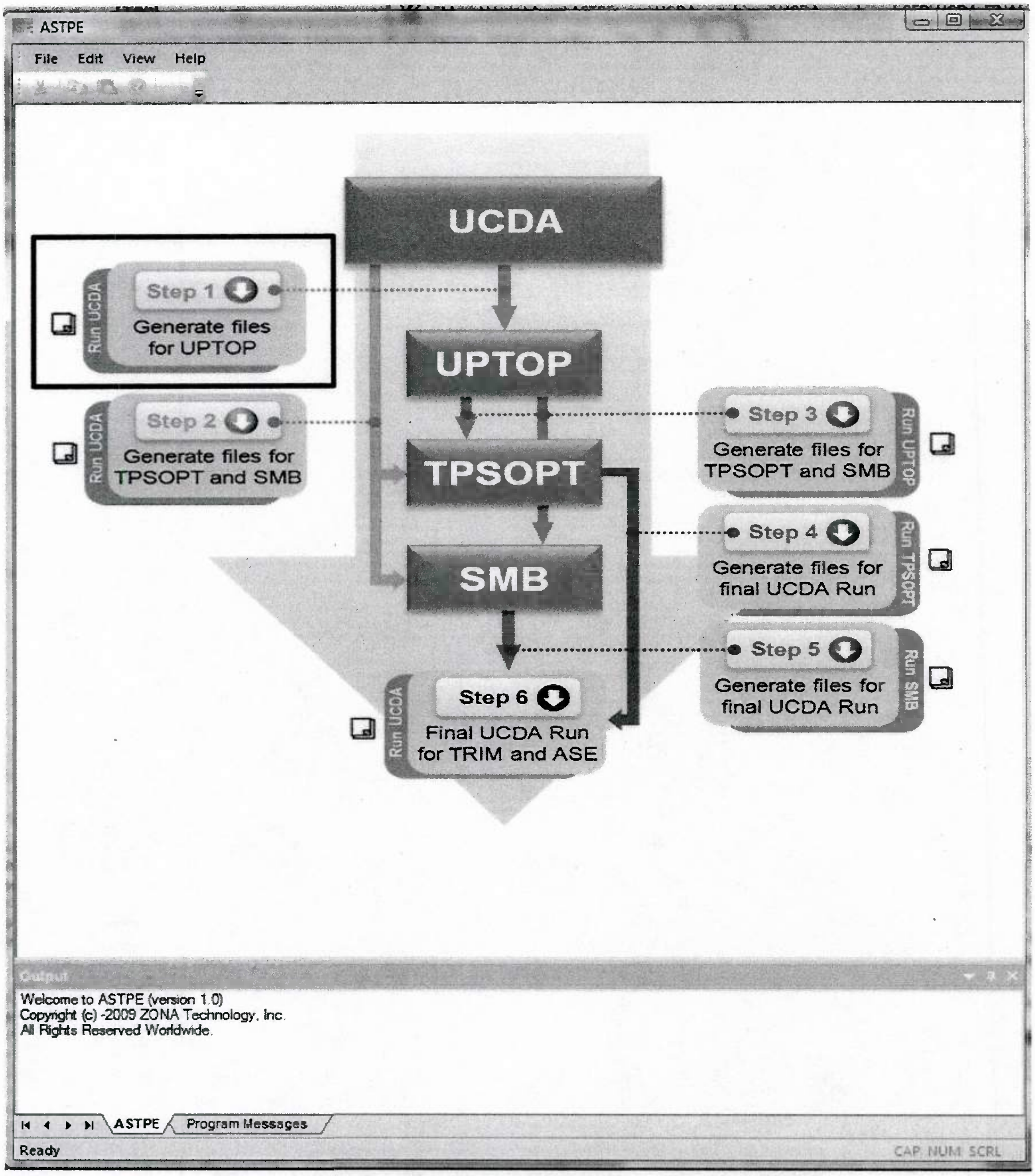


Figure 9.3.1 Section Corresponding to Step 1 of GUI

9.3.1 Generate Tab Files

Input Files:

File Name	Type	Remarks	See Listing
vehicle.inp	Standard input file	Also look at Table 9.3.1a 9.3.1.b	Shown in Listing 9.3.1
chem.bin	Engine chemistry information	Required	Shown in Listing 9.2.2
SEDvehicle.inp	Standard input file for SED type vehicle	Required	Shown in Listing 9.2.3

Output Files:

File Name	Type	Remarks	See Listing
lift.tab	Tabular format	Aerodynamic information for UPTOP	Shown in Listing 9.3.2
drag.tab	Tabular format	Aerodynamic information for UPTOP	Shown in Listing 9.3.3
fuel.tab	Tabular format	Aerodynamic information for UPTOP	Shown in Listing 9.3.4
thr.tab	Tabular format	Aerodynamic information for UPTOP	Shown in Listing 9.3.5

Input File descriptions

vehicle.inp: See Listing 9.3.1 for the entire input file. The parts of the input file that are used to generate the tables for UPTOP are displayed in Tables 9.3.1a and 9.3.1b. Table 9.3.1a shows the necessary parameters to control the creation of such tables and Table 9.3.1b shows a matrix of trajectory points. It can be noted that to generate tables for UPTOP, **itrajectory** has to be set to **2** and **offdesign.dat** switch has to be set to **2**. These are the only change needed from the earlier run of Section 9.2.

Different points on the trajectory are defined by the way shown in Table 9.3.1b. There are six lines in Table 9.3.1b. Each line has its own parameter such as altitude, dynamic pressure, throttle etc. Since **ialtdyn** is set to **2** (Table 9.3.1a), the code does not need to run corresponding to the altitude. Also, since **ithrottle** is set to **1**, the line with the Equivalence ratio is not used. More discussions on this can be found in the User's Manual. Thus, the code goes through the rest of the four variables. Each variable has got its lower bound and upper bound defined in the first and third number from the left. Also, the fifth variable is the value of its interval. For

example, for Mach number, the lower bound is 6.0, upper bound is 8.0 and interval is 0.5. Thus, the code will run through 5 points for Mach number. Similarly, each of these four parameters has such bounds and intervals. Thus, the code runs a combination of all possible points, which is a total of 3 dynamic pressure points x 11 throttle points x 5 mach number points x 11 angle of attack points = 1815 points.

chem.bin: This file remains the same for all UCDA runs. Please see Section 9.2 for description on this file.

SEDvehicle.inp: This file remains the same for all SED runs. Please see Section 9.2 for description on this file.

Table 9.3.1a Necessary Blocks Controlling TAB File Creation for UPTOP

```
TEST INPUT DECK:  Note - this line must be here!
2        ialtdyn - Inlet specified alt. (0), Fixed alt. (1), or Fixed dyn. press. (2)
1        ithrottle - Run engine as a function of: (0) equivalence ratio, (1) % throttle, (2) max throttle
1        iunits - Output unit switch: SI (1) or English (2)
3        ivisc - Viscous flag: inviscid (1), laminar (2), transitional (3), turbulent (4)
1        iequiv - find max equiv ratio for choked flow: off (0) -> single run, on (1)
2        inozorder - Nozzle polynomial order: 1st (flat plate) -> 3rd
1        iheight - Height constrained vehicle: no (0) = linlet set, yes (1) = height set
2        itrajectory - Run multiple trajectory points: no (0), discrete (1), matrix (2)
0        icone - cone flow data: exact (0), curve-fit approximation (1)
4        imodel - Forebody type: WA (1), VWA (2), VWA + cone flow (3), or SED (4)
0        itrim - Control surface deflection to trim the vehicle: no (0), yes (1), or optimize (2)
0        ideriv - Calculate derivatives: no (0), yes (1)
0        itps - If itps is 1, then prepare for tps and smb. ideriv and itps cannot be 1 at one time
0        ifeedback - If 1, then gets weight and Cg information from SMB and TPSOPT

OUTPUT FILE SWITCHES AND NAMES:
0  'plot.dat'            VEHICLEFIG:     off (0), select (1), x,y,z (2), all (3)
3 1 2 3 8 18 23   1st # -> # of variables to read, others -> vars to plot
0  'metrics.dat'         METRICS:        off (0), on-real (1), on-cmplx (2)
0  'cowlexit.dat'        COWLEXIT:       off (0), on (1)
0  'moc.dat'             NOZFIG: off (0), P,T,M (1), all (2)
2  'offdesign.dat'       AOA:            off (0), on (1), UPTOP input tables (2), UPTOP input files (3)
0  'scramjet.dat'        CKENGINE:       off (0), on (1)
0                        IPRINTINLET:    off (0), all (1), results (2), all-real (3), results-real (4)
0                        IPRINTENGINE:   off (0), on (1)
0                        IDEBUG: off (0), on (1) [print debugging info]
```

Table 9.3.1b Necessary Blocks to Run a Matrix of Points to Generate Table

```
INPUT DATA:  (0 = degrees, 1 = m, 2 = ft, 3 = atm, 4 = dimensionless, K or kg, 5 = psf)
xl       x        xu       unit     res      name
22500.   26290.   30000.   1        2500.    'altitude' - altitude (if required)
```

1500.	1700.	2000.0	5	250.	'q0' - dynamic pressure (if required)
.50	1.0299	1.0	4	.250	'equiv' - equivalence ratio
1.	1.0	0.0	4	-.10	'throttle' - engine throttle (if required)
6.0	7.0	8.00	4	.5	'm0' - Mach number
-2.00	0.0	3.00	0	.5	'AOA' - angle of attack

Output File Descriptions

lift.tab: For each of the points described above, lift is tabulated in this file. Please see Listing 9.3.2.

drag.tab: For each of the points described above, drag is tabulated in this file. Please see Listing 9.3.3.

fuel.tab: For each of the points described above, fuel is tabulated in this file. Please see Listing 9.3.4.

thr.tab: For each of the points described above, thrust is tabulated in this file. Please see Listing 9.3.5.

UPTOP requires these four tabulated results to find the optimized trajectory.

The computational run time to generate the *.tab files for UPTOP is approximately 30 minutes for sample SED.

9.3.2 Generate Input Files

Input Files:

File Name	Type	Remarks	See Listing
vehicle.inp	Standard input file	Also look at Table 9.3.2	Shown in Listing 9.3.6
chem.bin	Engine chemistry information	Required and does not change	Shown in Listing 9.2.2
SEDvehicle.inp	Standard input file for SED type vehicle	Require and does not change	Shown in Listing 9.2.3

Output Files:

File Name	Type	Remarks	See Listing
traj.inp	Standard input for UPTOP	Main input file for UPTOP	Shown in Listing 9.3.7
model.inp	Standard input for UPTOP	Information about model	Shown in Listing 9.3.8

Input File Descriptions

vehicle.inp: See Listing 9.3.6 for the entire input file. The part of the input file that is used to generate the input files model.inp and traj.inp for UPTOP is shown in Tables 9.3.2. It can be seen comparing Listings 9.3.1 and 9.3.6 that the only changes between these two vehicle.inps are in the parameters **itrajectory** and **offdesign.dat** file switch. For the generation of the *.tab files, **itrajectory** was set to **2**. Here, as noted in Table 9.3.2, **itrajectory** is set to **0**. The flag for **offdesign.dat** is changed to **3** from **2**. These changes will generate model.inp and traj.inp.

Table 9.3.2: Changes in Input from Table 9.3.1a for Generating INP Files

```
TEST INPUT DECK:  Note - this line must be here!
2       ialtdyn - Inlet specified alt. (0), Fixed alt. (1), or Fixed dyn. press. (2)
1       ithrottle - Run engine as a function of: (0) equivalence ratio, (1) % throttle, (2) max throttle
1       iunits - Output unit switch: SI (1) or English (2)
3       ivisc - Viscous flag: inviscid (1), laminar (2), transitional (3), turbulent (4)
1       iequiv - find max equiv ratio for choked flow: off (0) -> single run, on (1)
2       inozorder - Nozzle polynomial order: 1st (flat plate) -> 3rd
1       iheight - Height constrained vehicle: no (0) = linlet set, yes (1) = height set
0       itrajectory - Run multiple trajectory points: no (0), discrete (1), matrix (2)
0       icone - cone flow data: exact (0), curve-fit approximation (1)
4       imodel - Forebody type: WA (1), VWA (2), VWA + cone flow (3), or SED (4)
0       itrim - Control surface deflection to trim the vehicle: no (0), yes (1), or optimize (2)
0       ideriv - Calculate derivatives: no (0), yes (1)
0       itps - If itps is 1, then prepare for tps and smb. ideriv and itps cannot be 1 at one time
```

```
0          ifeedback - If 1, then gets weight and Cg information from SMB and TPSOPT

OUTPUT FILE SWITCHES AND NAMES:
0  'plot.dat'              VEHICLEFIG:      off (0), select (1), x,y,z (2), all (3)
3 1 2 3 8 18 23     1st # -> # of variables to read, others -> vars to plot
0  'metrics.dat'           METRICS:         off (0), on-real (1), on-cmplx (2)
0  'cowlexit.dat'          COWLEXIT:        off (0), on (1)
0  'moc.dat'               NOZFIG:          off (0), P,T,M (1), all (2)
3  'offdesign.dat'         AOA:             off (0), on (1), UPTOP input tables (2), UPTOP input files (3)
0  'scramjet.dat'          CKENGINE:        off (0), on (1)
0                          IPRINTINLET:     off (0), all (1), results (2), all-real (3), results-real (4)
0                          IPRINTENGINE:    off (0), on (1)
0                          IDEBUG:          off (0), on (1) [print debugging info]
```

Output File descriptions

traj.inp: See Listing 9.3.7 for this output. This file is the main input file for UPTOP. It contains information about orientation parameters, optimization parameters, event parameters, engine throttle control etc. Please see Section 4.5.1 of User's Manual for detailed description.

model.inp: See Listing 9.3.8 for this output that is used by UPTOP as a standard input file. This file contains information about number of components, engine, fuel tank etc. The detailed explanation of this file can be found in Section 4.5.4 of User's Manual.

The computational run time to generate the input files for UPTOP is about a few seconds.

Listing 9.3.1: Vehicle.inp Input File for UPTOP Tab File Generation

```
TEST INPUT DECK:  Note - this line must be here!
2          ialtdyn - Inlet specified alt. (0), Fixed alt. (1), or Fixed dyn. press. (2)
1          ithrottle - Run engine as a function of: (0) equivalence ratio, (1) % throttle, (2) max throttle
1          iunits - Output unit switch: SI (1) or English (2)
3          ivisc - Viscous flag: inviscid (1), laminar (2), transitional (3), turbulent (4)
1          iequiv - find max equiv ratio for choked flow: off (0) -> single run, on (1)
2          inozorder - Nozzle polynomial order: 1st (flat plate) -> 3rd
1          iheight - Height constrained vehicle: no (0) = linlet set, yes (1) = height set
2          itrajectory - Run multiple trajectory points: no (0), discrete (1), matrix (2)
0          icone - cone flow data: exact (0), curve-fit approximation (1)
4          imodel - Forebody type: WA (1), VWA (2), VWA + cone flow (3), or SED (4)
0          itrim - Control surface deflection to trim the vehicle: no (0), yes (1), or optimize (2)
0          ideriv - Calculate derivatives: no (0), yes (1)
0          itps - If itps is 1, then prepare for tps and smb. ideriv and itps cannot be 1 at one time
1          ifeedback - If 1, then gets weight and Cg information from SMB and TPSOPT

OUTPUT FILE SWITCHES AND NAMES:
0   'plot.dat'                   VEHICLEFIG:         off (0), select (1), x,y,z (2), all (3)
3 1 2 3 8 18 23       1st # -> # of variables to read, others -> vars to plot
0   'metrics.dat'           METRICS:  off (0), on-real (1), on-cmplx (2)
0   'cowlexit.dat'          COWLEXIT:           off (0), on (1)
0   'moc.dat'                    NOZFIG:   off (0), P,T,M (1), all (2)
2   'offdesign.dat'              AOA:                off (0), on (1), UPTOP input tables (2), UPTOP input files (3)
0   'scramjet.dat'          CKENGINE: off (0), on (1)
0                                IPRINTINLET:        off (0), all (1), results (2), all-real (3), results-real (4)
0                                IPRINTENGINE:       off (0), on (1)
0                                IDEBUG:           off (0), on (1) [print debugging info]

ZONE DATA AND GRID SIZES:
```

```
21        NUMBER OF ZONES
'forebody : top'             3        3
'keel : top'                 3        3
'aftbody : top'              3        3
'forebody : bot'             31       31
'ramps : bot'                55       6
'comb : bot'                 101      6
'cowl : top'                 101      6
'nozzle : bot'               31       6
'ramp walls : inside'        35       6
'comb wall : inside'         101      7
'nozzle wall : inside'       21       7
'aftbody : bot'              101      31
'cowl : bot'                 101      6
'ramp walls : outside'       35       6
'comb wall : outside'        101      7
'nozzle wall : outside'      21       7
'SEDbody : top'              121      46
'Control_1 : top'            31       31   (Control surface dimensions must be the same)
'Control_1 : bottom'         31       31   (Control surface dimensions must be the same)
'Control_2 : top'            31       31   (Control surface dimensions must be the same)
'Control_2 : bottom'         31       31   (Control surface dimensions must be the same)

INPUT DATA:  (0 = degrees, 1 = m, 2 = ft, 3 = atm, 4 = dimensionless, K or kg, 5 = psf)
Xl        x         xu        unit      res        name
22500.    26290.    30000.    1         2500.      'altitude' - altitude (if required)
1500.     1700.     2000.0    5          250.      'q0'       - dynamic pressure (if required)
.50       1.0299    1.0       4         .250       'equiv'    - equivalence ratio
1.         1.0      0.0       4         -.10       'throttle' - engine throttle (if required)
6.0       7.0       8.00      4           .5       'm0'       - Mach number
-2.00     0.0       3.00      0           .5       'AOA'      - angle of attack
5.0       4         'Mdes'       - design Mach number
0.2935    0         'AOAdes'     - design angle of attack
26000.    1         'Zdes'       - design altitude
6.2672    1         'lvehicle'   - vehicle length
5.5939    0         'thforclu'   - forebody upper surface angle
3.8700    0         'thforcll'   - forebody ramp angle
0.5873    1         'lcontrol'   - control surface length
5.0       0         'th_control'- control surface deflection angle
0.9920    0         'th_expn'    - nozzle initial expansion angle
10.8958   0         'th_exit'    - nozzle exit angle
0.0       4         'p_nozpoly' - % diff between nozzle designs [DON'T USE-defaulted to 1.]
2.901     1         'lcowl'      - cowl length (isolator/combustor)
.3        1         'lcowlext'  - cowl extension length (internal nozzle)
0.545     4         'p_iso'      - percent of lcowl that is isolator
.3238     1         'height'     - height of vehicle (if required)
20.0      1         'linlet'     - inlet length of vehicle (if required)
.28       1         'wengine'    - width of the engine (currently defaulted to unit width)
3.00      4         'iramps'     - number of inlet ramps in addition to the forebody
4.4615    0         'th_ramp1'   - inlet ramp 1 angle
5.1567    0         'th_ramp2'   - inlet ramp 2 angle
5.9844    0         'th_ramp3'   - inlet ramp 3 angle
0.0       0         'th_ramp4'   - inlet ramp 4 angle
0.0       0         'th_ramp5'   - inlet ramp 5 angle
3.09      0         'th_div1'    - first combustor expansion angle
1.2       0         'th_div2'    - second combustor expansion angle
0.01      1         'Xinjs'        - beginning of injectors (m)
0.02      1         'Xinje'      - end of injectors (m)
0.01      1         'Lmix'       - fuel mixing length (m)
1.00      4         'eta_mix'    - fuel mixing and burning efficiency
4000.     4         'Tlimit'     - maximum engine temperature (K)
90.       0         'Thetainj'   - injector angle (degrees) [90 deg. is normal to flow]
1200.     4         'Tw'         - adiabatic wall temperature (K)
0.1527    4         'nfor'       - forebody exponent n
2.0       2         'wfor'       - forebody width
2.0       1         'lfor'       - forebody length
0.2427    4         'mfor'       - forebody exponent m
5.797     0         'thforle'    - forebody leading edge angle
21.519    0         'th_le'      - leading edge attachment angle
0.0000    4         'p_kl'       - keel-line height percentage
0.25      4         'fuelfrac'   - vehicle fuel volume fraction
0.0104    2         't_plate'    - shell plate thickness (Tungsten)
0.00000   4         'mass_smb'   - mass due to Structural Modal Base (SMB) analysis
0.00000   4         'mass_tps'   - mass due to Thermal Protection System (TPS) analysis
0.00000   4         'mass_nose' - mass due to Thermal Protection System (TPS) analysis
```

Listing 9.3.2: Lift.tab Output File From UCDA / Input File for UPTOP

```
1
           4
           3          10
           5          11
          11          30
          11         201
 1 0
   71820.38
   83790.45
```

```
  95760.52
  6.000000
  6.500000
  7.000000
  7.500000
  8.000000
 -2.000000
 -1.500000
 -1.000000
-0.5000000
 0.0000000E+00
 0.5000000
  1.000000
  1.500000
  2.000000
  2.500000
  3.000000
  1.000000
 0.9000000
 0.8000000
 0.7000000
 0.6000000
 0.5000000
 0.4000000
 0.3000000
 0.2000000
 9.9999987E-02
-1.4901161E-08
-8.5015129E-03
-8.8613592E-03
-9.2074331E-03
-8.9160744E-03
-9.3178777E-03____
----
----
......
 6.7598328E-02
 6.5432645E-02
 6.3360982E-02
 6.2609807E-02
 5.9198547E-02
 8.1768841E-02
 8.1367888E-02
 7.8875162E-02
 8.0384992E-02
 7.8386605E-02
 7.5742245E-02
 7.3862076E-02
 7.1785584E-02
 7.0098795E-02
 6.8872631E-02
 6.6135794E-02
 8.7031588E-02
 8.6279862E-02
 8.4007591E-02
 8.5276090E-02
 8.3665103E-02
 8.1361860E-02
 7.9045452E-02
 7.7917948E-02
 7.4844934E-02
 7.4751720E-02
 7.2875395E-02
```

Listing 9.3.3: Drag.tab Output File From UCDA / Input File for UPTOP

```
1
           4
           3          10
           5          11
          11          30
          11         201
 1 0
  71820.38
  83790.45
  95760.52
  6.000000
  6.500000
  7.000000
  7.500000
  8.000000
 -2.000000
 -1.500000
 -1.000000
-0.5000000
 0.0000000E+00
 0.5000000
  1.000000
  1.500000
  2.000000
```

```
   2.500000
   3.000000
   1.000000
  0.9000000
  0.8000000
  0.7000000
  0.6000000
  0.5000000
  0.4000000
  0.3000000
  0.2000000
  9.9999987E-02
 -1.4901161E-08
  4.1842587E-02
  4.1646343E-02
----
----
----
----
  8.9965522E-02
  8.6033843E-02
  8.2398944E-02
  7.9125471E-02
  7.6165535E-02
  7.3558360E-02
  7.1296528E-02
  6.9357380E-02
  6.7708887E-02
  0.1153808
  0.1095439
  0.1044403
  9.9838257E-02
  9.5641494E-02
  9.1779627E-02
  8.8255912E-02
  8.5131563E-02
  8.2363270E-02
  7.9952553E-02
  7.7863649E-02
```

Listing 9.3.4: Fuel.tab Output File From UCDA / Input File for UPTOP

```
1
           4
           3          10
           5          11
          11          30
          11         201
 1 0
   71820.38
   83790.45
   95760.52
   6.000000
   6.500000
   7.000000
   7.500000
   8.000000
  -2.000000
  -1.500000
  -1.000000
 -0.5000000
  0.0000000E+00
  0.5000000
   1.000000
   1.500000
   2.000000
   2.500000
   3.000000
   1.000000
  0.9000000
  0.8000000
  0.7000000
  0.6000000
  0.5000000
  0.4000000
  0.3000000
  0.2000000
  9.9999987E-02
 -1.4901161E-08
  0.7388166
  0.6649349
----
----
----
  0.4570374
  0.3917464
  0.3264553
  0.2611642
```

```
 0.1958732
 0.1305821
 6.5291047E-02
-9.7291259E-09
 0.6349592
 0.5714633
 0.5079674
 0.4444714
 0.3809755
 0.3174796
 0.2539837
 0.1904878
 0.1269918
 6.3495912E-02
-9.4616297E-09
 0.5978621
 0.5380759
 0.4782897
 0.4185035
 0.3587173
 0.2989311
 0.2391448
 0.1793586
 0.1195724
 5.9786201E-02
-8.9088399E-09
```

Listing 9.3.5: Thr.tab Output File From UCDA / Input File for UPTOP

```
1
           4
           3          10
           5          11
          11          30
          11         201
 1 0
   71820.38
   83790.45
   95760.52
   6.000000
   6.500000
   7.000000
   7.500000
   8.000000
  -2.000000
  -1.500000
  -1.000000
 -0.5000000
  0.0000000E+00
  0.5000000
   1.000000
   1.500000
   2.000000
   2.500000
   3.000000
   1.000000
  0.9000000
  0.8000000
  0.7000000
  0.6000000
  0.5000000
  0.4000000
  0.3000000
  0.2000000
  9.9999987E-02
 -1.4901161E-08
   1.230211
   1.218165
-----
-----
-----
   2.241872
   2.116534
   2.008070
   1.903508
   4.012670
   3.756747
   3.533950
   3.335721
   3.138714
   2.954617
   2.783321
   2.624865
   2.481252
   2.353849
   2.235506
   4.541084
   4.268238
   4.019526
   3.797655
```

```
3.585260
3.383832
3.194473
3.022392
2.860141
2.720629
2.591109
```

Listing 9.3.6: Vehicle.inp Input File for UPTOP Input (INP) File Generation

```
TEST INPUT DECK:  Note - this line must be here!
2         ialtdyn - Inlet specified alt. (0), Fixed alt. (1), or Fixed dyn. press. (2)
1         ithrottle - Run engine as a function of: (0) equivalence ratio, (1) % throttle, (2) max throttle
1         iunits - Output unit switch: SI (1) or English (2)
3         ivisc - Viscous flag: inviscid (1), laminar (2), transitional (3), turbulent (4)
1         iequiv - find max equiv ratio for choked flow: off (0) -> single run, on (1)
2         inozorder - Nozzle polynomial order: 1st (flat plate) -> 3rd
1         iheight - Height constrained vehicle: no (0) = linlet set, yes (1) = height set
0         itrajectory - Run multiple trajectory points: no (0), discrete (1), matrix (2)
0         icone - cone flow data: exact (0), curve-fit approximation (1)
4         imodel - Forebody type: WA (1), VWA (2), VWA + cone flow (3), or SED (4)
0         itrim - Control surface deflection to trim the vehicle: no (0), yes (1), or optimize (2)
0         ideriv - Calculate derivatives: no (0), yes (1)
0         itps - If itps is 1, then prepare for tps and smb. ideriv and itps cannot be 1 at one time
1         ifeedback - If 1, then gets weight and Cg information from SMB and TPSOPT

OUTPUT FILE SWITCHES AND NAMES:
0   'plot.dat'                         VEHICLEFIG:        off (0), select (1), x,y,z (2), all (3)
3 1 2 3 8 18 23        1st # -> # of variables to read, others -> vars to plot
0   'metrics.dat'             METRICS:  off (0), on-real (1), on-cmplx (2)
0   'cowlexit.dat'            COWLEXIT:           off (0), on (1)
0   'moc.dat'                          NOZFIG:   off (0), P,T,M (1), all (2)
3   'offdesign.dat'                    AOA:               off (0), on (1), UPTOP input tables (2), UPTOP input files (3)
0   'scramjet.dat'            CKENGINE: off (0), on (1)
0                                      IPRINTINLET:       off (0), all (1), results (2), all-real (3), results-real (4)
0                                      IPRINTENGINE:      off (0), on (1)
0                                      IDEBUG:          off (0), on (1) [print debugging info]

ZONE DATA AND GRID SIZES:
21        NUMBER OF ZONES
'forebody : top'            3        3
'keel : top'                3        3
'aftbody : top'             3        3
'forebody : bot'            31       31
'ramps : bot'               55       6
'comb : bot'                101      6
'cowl : top'                101      6
'nozzle : bot'              31       6
'ramp walls : inside'       35       6
'comb wall : inside'        101      7
'nozzle wall : inside'      21       7
'aftbody : bot'             101      31
'cowl : bot'                101      6
'ramp walls : outside'      35       6
'comb wall : outside'       101      7
'nozzle wall : outside'     21       7
'SEDbody : top'             121      46
'Control_1 : top'           31       31   (Control surface dimensions must be the same)
'Control_1 : bottom'        31       31   (Control surface dimensions must be the same)
'Control_2 : top'           31       31   (Control surface dimensions must be the same)
'Control_2 : bottom'        31       31   (Control surface dimensions must be the same)

INPUT DATA:  (0 = degrees, 1 = m, 2 = ft, 3 = atm, 4 = dimensionless, K or kg, 5 = psf)
Xl        x         xu        unit      res       name
22500.    26290.    30000.    1         2500.     'altitude' - altitude (if required)
1500.     1700.     2000.0    5          250.     'q0'       - dynamic pressure (if required)
.50       1.0299    1.0       4         .250      'equiv'    - equivalence ratio
1.         1.0      0.0       4         -.10      'throttle' - engine throttle (if required)
6.0       7.0       8.00      4           .5      'm0'       - Mach number
-2.00     0.0       3.00      0           .5      'AOA'      - angle of attack
5.0       4         'Mdes'      - design Mach number
0.2935    0         'AOAdes'    - design angle of attack
26000.    1         'Zdes'      - design altitude
6.2672    1         'lvehicle'  - vehicle length
5.5939    0         'thforclu'  - forebody upper surface angle
3.8700    0         'thforcll'  - forebody ramp angle
0.5873    1         'lcontrol'  - control surface length
5.0       0         'th_control'- control surface deflection angle
0.9920    0         'th_expn'   - nozzle initial expansion angle
10.8958   0         'th_exit'   - nozzle exit angle
0.0       4         'p_nozpoly' - % diff between nozzle designs [DON'T USE-defaulted to 1.]
2.901     1         'lcowl'     - cowl length (isolator/combustor)
.3        1         'lcowlext'  - cowl extension length (internal nozzle)
0.545     4         'p_iso'     - percent of lcowl that is isolator
.3238     1         'height'    - height of vehicle (if required)
20.0      1         'linlet'    - inlet length of vehicle (if required)
.28       1         'wengine'   - width of the engine (currently defaulted to unit width)
3.00      4         'iramps'    - number of inlet ramps in addition to the forebody
4.4615    0         'th_ramp1'  - inlet ramp 1 angle
5.1567    0         'th_ramp2'  - inlet ramp 2 angle
5.9844    0         'th_ramp3'  - inlet ramp 3 angle
0.0       0         'th_ramp4'  - inlet ramp 4 angle
```

```
0.0       0         'th_ramp5'  - inlet ramp 5 angle
3.09      0         'th_div1'   - first combustor expansion angle
1.2       0         'th_div2'   - second combustor expansion angle
0.01      1         'Xinjs'       - beginning of injectors (m)
0.02      1         'Xinje'     - end of injectors (m)
0.01      1         'Lmix'      - fuel mixing length (m)
1.00      4         'eta_mix'   - fuel mixing and burning efficiency
4000.     4         'Tlimit'    - maximum engine temperature (K)
90.       0         'Thetainj'  - injector angle (degrees) [90 deg. is normal to flow]
1200.     4         'Tw'        - adiabatic wall temperature (K)
0.1527    4         'nfor'      - forebody exponent n
2.0       2         'wfor'      - forebody width
2.0       1         'lfor'      - forebody length
0.2427    4         'mfor'      - forebody exponent m
5.797     0         'thforle'   - forebody leading edge angle
21.519    0         'th_le'     - leading edge attachment angle
0.0000    4         'p_kl'      - keel-line height percentage
0.25      4         'fuelfrac'  - vehicle fuel volume fraction
0.0104    2         't_plate'   - shell plate thickness (Tungsten)
0.00000   4         'mass_smb'  - mass due to Structural Modal Base (SMB) analysis
0.00000   4         'mass_tps'  - mass due to Thermal Protection System (TPS) analysis
0.00000   4         'mass_nose' - mass due to Thermal Protection System (TPS) analysis
```

Listing 9.3.7: Traj.inp Output File From UCDA / Input File for UPTOP

```
RUN METHOD
 10  (0-single case, 1-new GA, 2-restart, 3-mapspace)

INITIAL CONDITIONS
-----------------------------------------------------------------------------
 1  25230.2  22406.8  28053.7  initial altitude (m)
 0      0.0    -10.0     10.0  initial gamma
 1     -6.2     -8.0     -6.0  initial velocity (m/s)

ORIENTATION PARAMETERS
2  Mode (1 - rpy, 2 - aeroballistic angles)
-----------------------------------------------------------------------------
 30  angle 1 id
 0  Variable Mode
 1  Curve fit order
 1  Independent Variable type
 2  Number of Control Points
  0  0    0.0    1.0   10.0
  0  0  500.0    1.0   10.0
  1  0   -1.5   -2.0    3.0
  1  0   -1.0   -2.0    3.0

 32  angle 1 id
 2  Variable Mode
 0  0  0  0

 31  angle 1 id
 2  Variable Mode
 0  0  0  0

TRAJECTORY EVENTS
 0  Number of Control Points
-----------------------------------------------------------------------------

THROTTLE CONTROLS
 1  Number of engine specifications
 -----------
 1  Engine Number
 2  Specification Type
 0  1  0  0

TERMINATION PARAMETERS
-----------------------------------------------------------------------------
 0  0  -551  1.  0  0

NAVIGATION PARAMETERS
-----------------------------------------------------------------------------
 0  0.   0.  10.   mu
 0  0.   0.  10.   longitude
 0  90.  0.  10.   heading

THRUST
 1
-----------------------------------------------------------------------------
 1
 1
 thr.tab

 1
 fuel.tab

VARIABLE TRACKING
 1  Number of Variables to Track
-----------------------------------------------------------------------------
 2      6       0       0       0       -1

OPTIMIZATION AND CONSTRAINT PARAMETERS
```

```
--------------------------------------------------------------------------------
 1  Number of Optimization Variables
 58  1  .001  0  -1.  0.

 2  Number of Constraint Variables
 1001      1   1.00   0  -1.00   0        0.0000   1000.0000       0.0000
 1001     -1   1.00   0  -1.00   0        0.0000   1000.0000       0.0000

IO FILES
 1                            number of output files
--------------------------------------------------------------------------------
 3 5       output format, number of output variables
 1                    del(time) if >0; stride if <0
 1 11 2 30 32       variable ids (from varlist.txt)
 trajct.dat              output filename
```

Listing 9.3.8: Model.inp Output File from UCDA / Input File for UPTOP

```
GENERAL INFORMATION
 1       Number of vehicle components

 Stage/Component Linking
#num     no comps  component numbers
 1  1  1

 Stage Reference Areas
 0    3.658696      0.  0.  stage(1)

 Nose Radus
 0   6.4000001E-06   0.  100.

 VEHICLE COMPONENT PARAMETERS
 ***** Component 1 Information *****
 0    1022.317      0. 0. Dry Vehicle Mass (kilograms)

 Engine Information
 1   Total Number of Engines groups
--------------------------------------------------------------------------------
 1
 0 0
 0   9.8661505E-02  0  0   engine area

 Fuel Tank Information
 1  Total Number of Fuel Tanks
--------------------------------------------------------------------------------
 1
 0   254.6685      0.  0.

 ENGINE/TANK LINKING
 1  Total number of links
 engine        tank
 1  1
```

9.4 Run UPTOP to Generate Optimized Trajectory for Use in TPSOPT and SMB

This section corresponds to the Step 3 in the Graphical User Interface (GUI). See Figure 9.4.1 below.

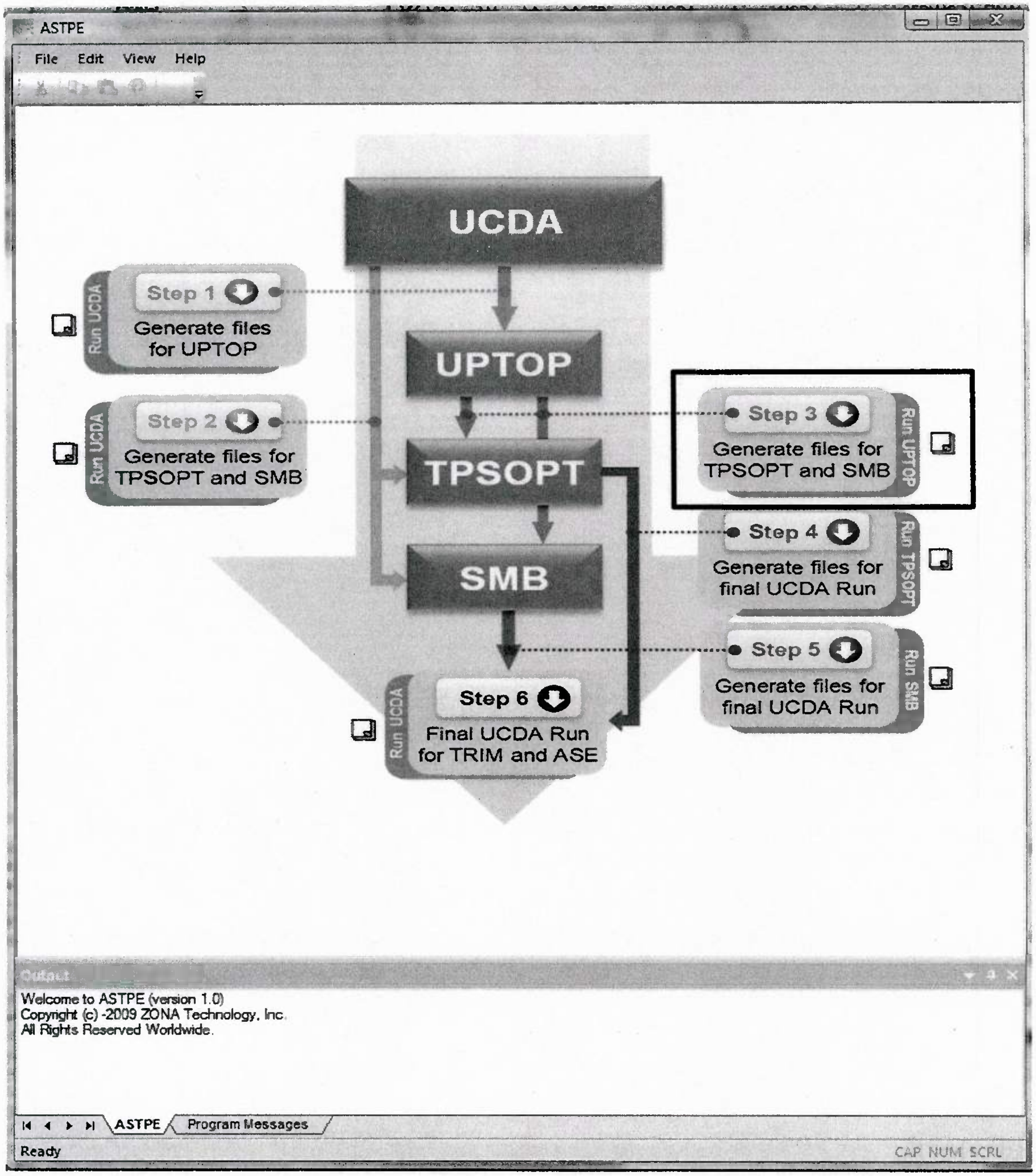


Figure 9.4.1 Section Corresponding to Step 3 of GUI

Input Files:

File Name	Type	Remarks	See Listing
des.inp	Standard input file	Required	Shown in Listing 9.4.1
params.inp	Standard input file	Required	Shown in Listing 9.4.2
traj.inp model.inp lift.tab drag.tab fuel.tab thr.tab	Input and Table files needed to generate optimized trajectory	Generated by UCDA (described in Section 9.3)	Shown in Listing 9.3.2-9.3.5,9.3.7-9.3.8

Output Files:

File Name	Type	Remarks	See Listing
trajct.dat	Optimized trajectory as input to TPSOPT and SMB	Time, Altitude, Angle of attack and Mach number information	Shown in Listing 9.4.3
output.dat	TECPLOT format	Plotted in Fig. 9.4.2	Not Shown

Input File descriptions

des.inp: See Listing 9.4.1 for des.inp input file to UPTOP. This file specifically caters to DES optimizer. If the optimization method is fixed, this input is fixed. Thus, this file is used for all the cases in ASTPE.

params.inp: See Listing 9.4.2 for params.inp input file to UPTOP. This file contains different necessary parameters about trajectory, earth/orbit, optimization etc.

The details on each of these files are listed in the User's Manual (Sections 4.5.2 and 4.5.3).

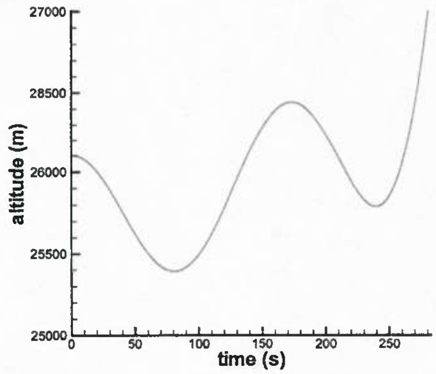
Output File descriptions

trajct.dat: See Listing 9.4.3 for this file. This file is a necessary input file for TPSOPT and SMB. Both TPSOPT and SMB need this file to compute heat flux and load respectively. The number

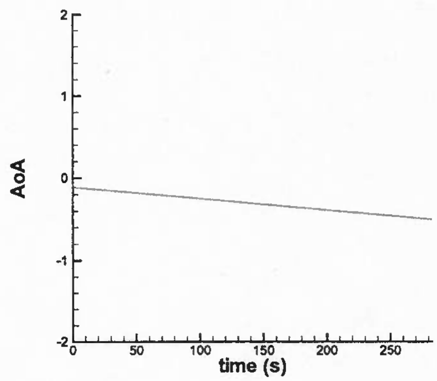
of points in trajct.dat is kept at 25 to maintain enough information about the trajectory without giving up computational efficiency.

output.dat: This is a TECPLOT format file and it contains optimized trajectory information. Figure 9.4.2 plots altitude, angle of attack and Mach number with respect to time using this file.

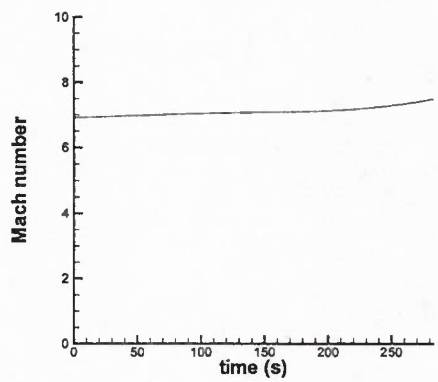
The computational time to finish this UPTOP run is approximately 60 minutes for sample SED.



(a) Altitude



(b) AoA



(c) Mach number

Figure 9.4.2 SED trajectory of Design Cycle 1

Listing 9.4.1: Des.inp UPTOP Input File

```
DES INPUTS
Run Control
-9                  Restart (0 - new run, 1- restart)
100                 Maximum Generations
0                   Convergence Criteria (# of generations without improvement)
-9        Stop when value reached

Input/Output Control
100                 restart file write frequency (number of generations)
-9                  screen output
1                   file output (0 - off/external, 1 - only rec. improvments, 2 - all)
10                  dvrec.out flush increment

Optimization Control
0         Pareto Optimization (0 - single obj fcn, 1 - Pareto-front optimzization)
0         random number seed (0 - fcn of date, else specify exact)
100       population size
0         Localization Switch
0.                  diversity threshold
0.                  diversity radius

DES Operator Parameters
1         number of differential terms (1-3)
-1        crossover probability (<0, 0-1)
-1        mutation intensity (<0, 0-1)
-1        coefficient of complex combination (<0, 0-1)

Supplemental Optimizer
2         optimizer switcb (0- none, 1- DHC, 2- DOT)
10        call frequency (< 0 = CVR, > 0 = # of generations)
0                   Maximum number of parallel calls
```

Listing 9.4.2: Params.inp UPTOP Input File

```
CODE PARAMETERS FILE
MODEL
0         Atmosphere Model (0- 1976 US Standard, 1- NRL model)
0         Rotating Earth
1         Speed of Sound (1- actual, 0-constant (sos at sea level))
1         Keep mass constant (0- constant mass, 1- fuel expended)

TRAJECTORY PARAMETERS
.1        Time Step
1000.     Maximum Time

COMPUTATION MODULES
1         Auxillary Calculation
1         Calculate Ranges
0         Calculate Orbital Parameters
0         Calculate Entry Parameters
0         Full Guidance Output

OPTIMIZATION PARAMETERS
0         optimization method
1         print progress (0 - no, 1 - debug single run, -1 - debug optimization)

OUTPUT PARAMETERS
0         screen output (0- off, 2- final output only, 1- all output)
0         increment value for output file (0 - default=1000)
0         print input to file
1         Tecplot header

CONSTANTS
9.80665   acceleration due to gravity (m/s)
6378.     radius of earth (km)
288.16    sea level temperature (K)
1.01325e5 sea level pressure (N/m^2)
1.225     sea level density (kg/m^3)
```

Listing 9.4.3: Trajct.dat UPTOP Output File that is used in TPSOPT and SMB

```
TRAJCT        100       10
              0.0  6.9200  26105.  -0.110
             12.0  6.9300  26068.  -0.130
             24.0  6.9400  25964.  -0.150
             36.0  6.9600  25815.  -0.160
             48.0  6.9700  25651.  -0.180
             60.0  6.9900  25507.  -0.200
             72.0  7.0100  25414.  -0.210
             84.0  7.0200  25395.  -0.230
             96.0  7.0300  25456.  -0.250
            108.0  7.0400  25590.  -0.260
            120.0  7.0500  25778.  -0.280
            132.0  7.0600  25990.  -0.300
            144.0  7.0700  26191.  -0.310
```

```
          156.0  7.0700  26347.   -0.330
          168.0  7.0800  26430.   -0.350
          180.0  7.0900  26425.   -0.360
          192.0  7.1000  26335.   -0.380
          204.0  7.1200  26181.   -0.400
          216.0  7.1500  26001.   -0.410
          228.0  7.1900  25850.   -0.430
          240.0  7.2300  25789.   -0.450
          252.0  7.2900  25878.   -0.460
          264.0  7.3500  26167.   -0.480
          276.0  7.4300  26694.   -0.500
          282.0  7.4700  27056.   -0.510         TECPLOT          1283.PLT
timesp  201           0.000  60.000 120.000 180.000 240.000 282.000
```

9.5 Run UCDA to Generate Mesh for TPSOPT and SMB

This section corresponds to the Step 2 in the Graphical User Interface (GUI). See Figure 9.5.1 below.

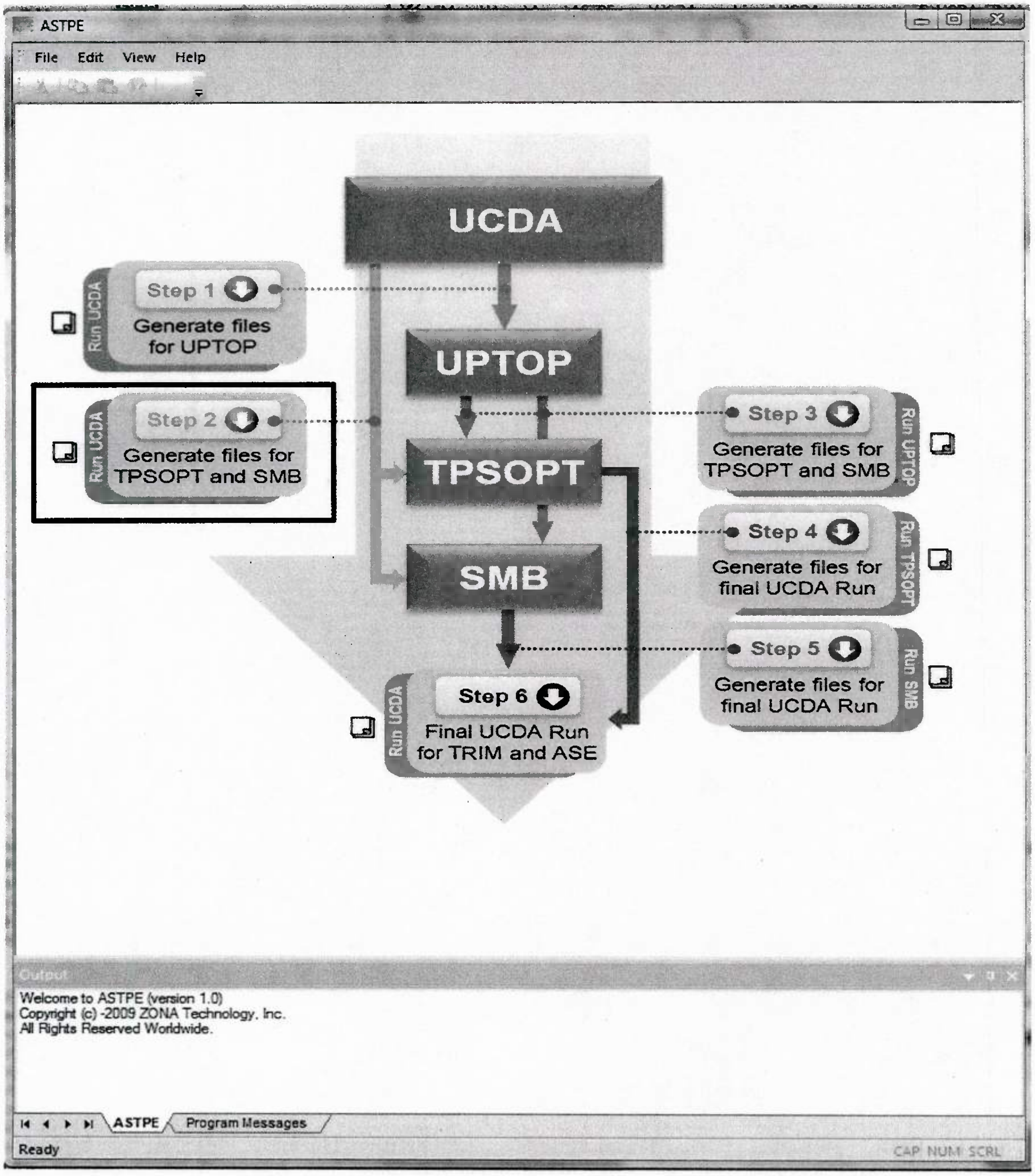


Figure 9.5.1 Section Corresponding to Step 2 of GUI

Input Files:

File Name	Type	Remarks	See Listing
vehicle.inp	Standard input file	Also look at Table 9.5.1	Shown in Listing 9.5.1
chem.bin	Engine chemistry information	Required	Shown in Listing 9.2.2
SEDvehicle.inp	Standard input file for SED type vehicle	Required	Shown in Listing 9.2.3

Output Files:

File Name	Type	Remarks	See Listing
geom_data.dat	unformatted	See Fig. 9.2.1	Not shown

Input File descriptions

vehicle.inp: See Listing 9.5.1 for the entire input file. The part of the input file that is used to command the code to generate mesh data for TPSOPT and SMB is shown in Table 9.5.1. It can be noted that **itps** is set to **1** in this case. This is the most important parameter to generate the mesh for TPSOPT and SMB. To run the code faster and only to output geometry information, **ideriv**, **itrajectory**, **itrim** are all set to **0**.

chem.bin: This file remains the same for all UCDA runs. Please see Section 9.2 for description on this file.

SEDvehicle.inp: This file remains the same for all SED runs. Please see Section 9.2 for description on this file.

Output File descriptions

geom_data.dat: This file is unformatted and thus it cannot be shown. It contains information such as grid points, panel ID, normal vector, area etc. The vehicle has been shown in Figure 9.2.1. This information is read into TPSOPT and SMB to compute heat flux and load respectively.

The computational run time for generating the geometry information is about a few seconds.

Table 9.5.1: Necessary Block on Vehicle.inp to Generate Geometry Information

TEST INPUT DECK: Note - this line must be here!	
2	ialtdyn - Inlet specified alt. (0), Fixed alt. (1), or Fixed dyn. press. (2)
1	ithrottle - Run engine as a function of: (0) equivalence ratio, (1) % throttle, (2) max throttle
1	iunits - Output unit switch: SI (1) or English (2)
3	ivisc - Viscous flag: inviscid (1), laminar (2), transitional (3), turbulent (4)
1	iequiv - find max equiv ratio for choked flow: off (0) -> single run, on (1)
2	inozorder - Nozzle polynomial order: 1st (flat plate) -> 3rd
1	iheight - Height constrained vehicle: no (0) = linlet set, yes (1) = height set
0	itrajectory - Run multiple trajectory points: no (0), discrete (1), matrix (2)
0	icone - cone flow data: exact (0), curve-fit approximation (1)
4	imodel - Forebody type: WA (1), VWA (2), VWA + cone flow (3), or SED (4)
0	itrim - Control surface deflection to trim the vehicle: no (0), yes (1), or optimize (2)
0	ideriv - Calculate derivatives: no (0), yes (1)
1	itps - If itps is 1, then prepare for tps and smb. ideriv and itps cannot be 1 at one time
0	ifeedback - If 1, then gets weight and Cg information from SMB and TPSOPT

Listing 9.5.1: Vehicle.inp Input File for TPS and SMB Geometry File Generation

```
TEST INPUT DECK:  Note - this line must be here!
2         ialtdyn - Inlet specified alt. (0), Fixed alt. (1), or Fixed dyn. press. (2)
1         ithrottle - Run engine as a function of: (0) equivalence ratio, (1) % throttle, (2) max throttle
1         iunits - Output unit switch: SI (1) or English (2)
3         ivisc - Viscous flag: inviscid (1), laminar (2), transitional (3), turbulent (4)
1         iequiv - find max equiv ratio for choked flow: off (0) -> single run, on (1)
2         inozorder - Nozzle polynomial order: 1st (flat plate) -> 3rd
1         iheight - Height constrained vehicle: no (0) = linlet set, yes (1) = height set
0         itrajectory - Run multiple trajectory points: no (0), discrete (1), matrix (2)
0         icone - cone flow data: exact (0), curve-fit approximation (1)
4         imodel - Forebody type: WA (1), VWA (2), VWA + cone flow (3), or SED (4)
0         itrim - Control surface deflection to trim the vehicle: no (0), yes (1), or optimize (2)
0         ideriv - Calculate derivatives: no (0), yes (1)
1         itps - If itps is 1, then prepare for tps and smb. ideriv and itps cannot be 1 at one time
1         ifeedback - If 1, then gets weight and Cg information from SMB and TPSOPT

OUTPUT FILE SWITCHES AND NAMES:
0   'plot.dat'                    VEHICLEFIG:         off (0), select (1), x,y,z (2), all (3)
3 1 2 3 8 18 23        1st # -> # of variables to read, others -> vars to plot
0   'metrics.dat'          METRICS:  off (0), on-real (1), on-cmplx (2)
0   'cowlexit.dat'         COWLEXIT:          off (0), on (1)
0   'moc.dat'                     NOZFIG:   off (0), P,T,M (1), all (2)
0   'offdesign.dat'               AOA:                off (0), on (1), UPTOP input tables (2), UPTOP input files (3)
0   'scramjet.dat'         CKENGINE: off (0), on (1)
0                                 IPRINTINLET:        off (0), all (1), results (2), all-real (3), results-real (4)
0                                 IPRINTENGINE:       off (0), on (1)
0                                 IDEBUG:           off (0), on (1) [print debugging info]

ZONE DATA AND GRID SIZES:
21        NUMBER OF ZONES
'forebody : top'             3        3
'keel : top'                 3        3
'aftbody : top'              3        3
'forebody : bot'             31       31
'ramps : bot'                55       6
'comb : bot'                 101      6
'cowl : top'                 101      6
'nozzle : bot'               31       6
'ramp walls : inside'        35       6
'comb wall : inside'         101      7
'nozzle wall : inside'       21       7
'aftbody : bot'              101      31
'cowl : bot'                 101      6
'ramp walls : outside'       35       6
'comb wall : outside'        101      7
'nozzle wall : outside'      21       7
'SEDbody : top'              121      46
'Control_1 : top'            31       31   (Control surface dimensions must be the same)
'Control_1 : bottom'         31       31   (Control surface dimensions must be the same)
'Control_2 : top'            31       31   (Control surface dimensions must be the same)
'Control_2 : bottom'         31       31   (Control surface dimensions must be the same)

INPUT DATA:  (0 = degrees, 1 = m, 2 = ft, 3 = atm, 4 = dimensionless, K or kg, 5 = psf)
```

```
Xl         x         xu        unit      res       name
22500.     26290.    30000.    1         2500.     'altitude' - altitude (if required)
1500.      1700.     2000.0    5          250.     'q0'       - dynamic pressure (if required)
.50        1.0299    1.0       4         .250      'equiv'    - equivalence ratio
1.          1.0      0.0       4         -.10      'throttle' - engine throttle (if required)
6.0        7.0       8.00      4           .5      'm0'       - Mach number
-2.00      0.0       3.00      0           .5      'AOA'      - angle of attack
5.0        4         'Mdes'        - design Mach number
0.2935     0         'AOAdes'      - design angle of attack
26000.     1         'Zdes'        - design altitude
6.2672     1         'lvehicle'    - vehicle length
5.5939     0         'thforclu'    - forebody upper surface angle
3.8700     0         'thforcll'    - forebody ramp angle
0.5873     1         'lcontrol'    - control surface length
5.0        0         'th_control'- control surface deflection angle
0.9920     0         'th_expn'     - nozzle initial expansion angle
10.8958    0         'th_exit'     - nozzle exit angle
0.0        4         'p_nozpoly' - % diff between nozzle designs [DON'T USE-defaulted to 1.]
2.901      1         'lcowl'       - cowl length (isolator/combustor)
.3         1         'lcowlext'    - cowl extension length (internal nozzle)
0.545      4         'p_iso'       - percent of lcowl that is isolator
.3238      1         'height'      - height of vehicle (if required)
20.0       1         'linlet'      - inlet length of vehicle (if required)
.28        1         'wengine'     - width of the engine (currently defaulted to unit width)
3.00       4         'iramps'      - number of inlet ramps in addition to the forebody
4.4615     0         'th_ramp1'    - inlet ramp 1 angle
5.1567     0         'th_ramp2'    - inlet ramp 2 angle
5.9844     0         'th_ramp3'    - inlet ramp 3 angle
0.0        0         'th_ramp4'    - inlet ramp 4 angle
0.0        0         'th_ramp5'    - inlet ramp 5 angle
3.09       0         'th_div1'     - first combustor expansion angle
1.2        0         'th_div2'     - second combustor expansion angle
0.01       1         'Xinjs'         - beginning of injectors (m)
0.02       1         'Xinje'       - end of injectors (m)
0.01       1         'Lmix'        - fuel mixing length (m)
1.00       4         'eta_mix'     - fuel mixing and burning efficiency
4000.      4         'Tlimit'      - maximum engine temperature (K)
90.        0         'Thetainj'    - injector angle (degrees) [90 deg. is normal to flow]
1200.      4         'Tw'          - adiabatic wall temperature (K)
0.1527     4         'nfor'        - forebody exponent n
2.0        2         'wfor'        - forebody width
2.0        1         'lfor'        - forebody length
0.2427     4         'mfor'        - forebody exponent m
5.797      0         'thforle'     - forebody leading edge angle
21.519     0         'th_le'       - leading edge attachment angle
0.0000     4         'p_kl'        - keel-line height percentage
0.25       4         'fuelfrac'    - vehicle fuel volume fraction
0.0104     2         't_plate'     - shell plate thickness (Tungsten)
0.00000    4         'mass_smb'    - mass due to Structural Modal Base (SMB) analysis
0.00000    4         'mass_tps'    - mass due to Thermal Protection System (TPS) analysis
0.00000    4         'mass_nose' - mass due to Thermal Protection System (TPS) analysis
```

9.6 Run TPSOPT for Optimizing the Thermal Protection System

Input Files:

File Name	Type	Remarks	See Listing
sed_tpsopt.inp	Standard input file	Required	Shown in listing 9.6.1
trajct.dat	Trajectory data generated by UPTOP	Inserted into the Standard input file sed_tpsopt.INP by the **INCLUDE** bulk data card	Shown in Listing 9.4.3
geom_data.dat	Aerodynamic mesh generated by UCDA	Imported by the ASSIGN AEROBASE executive control command	Not Shown

Output Files:

File Name	Type	Remarks	See Listing
sed_tpsopt.out	Standard output file	Print out results	Shown in Listing 9.6.2
AERO.PLT	TECPLOT file of aerodynamic mesh.	Generated by the **PLTAERO** bulk data card with ID=1	Not Shown
SED_TPS3.PLT	TECPLOT file containing the TPS thickness of each layers on the aerodynamic panel model	Generated by the **PLTTPS** bulk data card with ID=103	Not Shown
SED_TPS4.PLT	TECPLOT file containing the total TPS thickness on each aerodynamic panel model	Generated by the **PLTTPS** bulk data card with ID=-104	Not Shown
1283.PLT	TECPLOT file containing the heat flux at the last time step of the trajectory.	Generated by the **TRAJCT** bulk data card	Not shown
mass_tps.dat	Mass of the optimized TPS	Input file for UCDA to update the change of weight due to TPS	Shown in Listing 9.6.3

9.6.1 Descriptions of the Input File: sed_tpsopt.inp (Shown in Listing 9.6.1)

General description of Executive Control Section, Case Control Section and Bulk Data Section of TPSOPT input is given in the Users Manual (Sections 5.3 and 5.4). For sample SED, the TPSOPT input is described here.

The aerodynamic mesh of the SED configuration generated by UCDA is stored in the file "geom_data.dat" and imported into the TPSOPT module by the following executive control command:

ASSIGN AEROBASE = geom_data.dat

There is only one subcase defined in the case control command shown as follows:

TPSDES = 100

This case control command refers to a **TPSDES** bulk data card with ID = 100 in the Bulk Data Section. The interrelationship of all bulk data cards in the Bulk Data Section is presented in Figure 9.6.1.

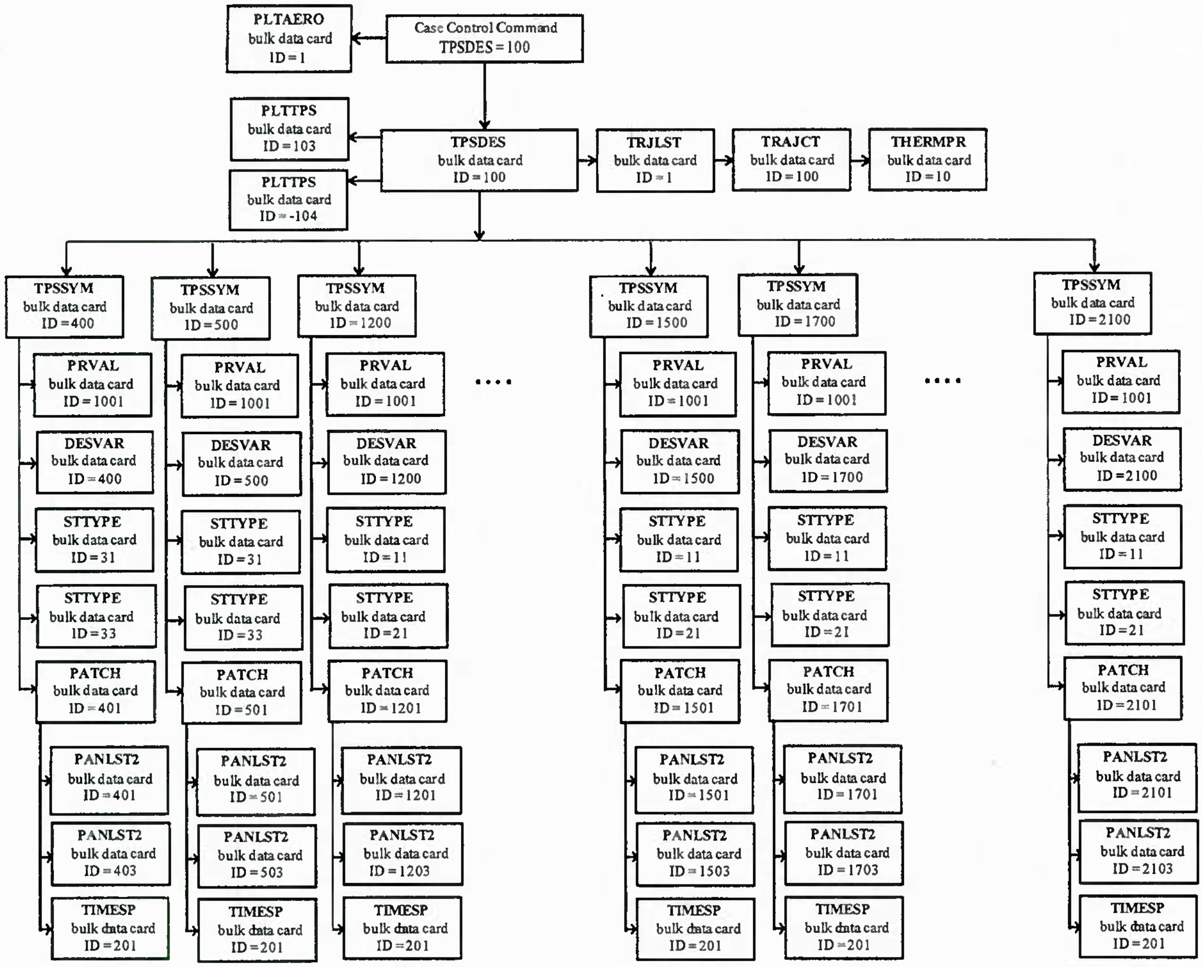


Figure 9.6.1 Interrelationship of All Bulk Data Cards for Optimizing the TPS for SED

The aerodynamic mesh generated by UCDA and imported by the ASSIGN AEROBASE = geom_data.dat executive control command can be visualized using the TECPLOT file "AERO.PLT" that is generated by a **PLTAERO** bulk data card with ID = 1. This aerodynamic mesh is shown in Figure 9.6.2.

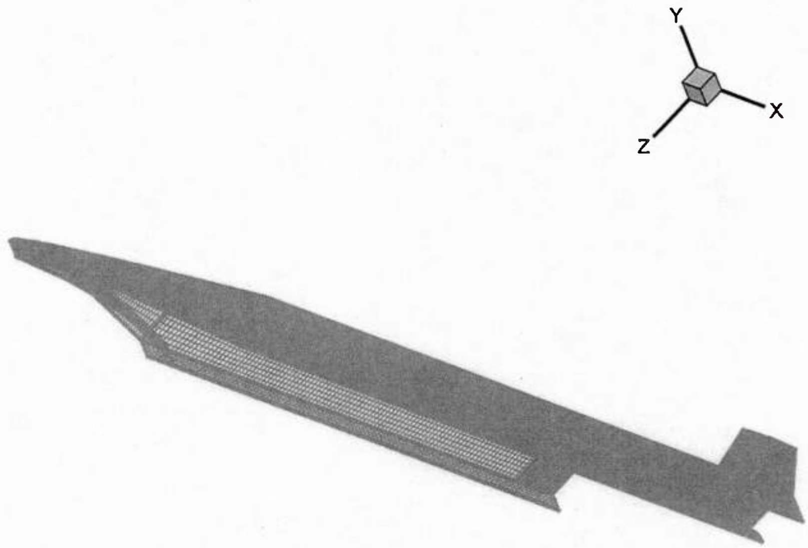


Figure 9.6.2 Visualization of Aerodynamic Mesh Using the PLTAERO bulk data card

There are 21 patches in the aerodynamic mesh but among them, only 8 patches with panel ID starting from 400001, 500001, 1200001, 1300001, 1400001, 1500001, 1700001, 1800001, 1900001, 2000001 and 2100001, respectively, are the outer surfaces and require the thermal protection system (TPS). Thus, the purpose of TPSOPT is to design the TPS system on those 11 patches for minimum TPS weight while satisfying the temperature constraints of each TPS layer as well as the load-carried structure. These temperature constraints are computed by integrating the heat flux on the outer surfaces along the trajectory generated by UPTOP. This trajectory is provided in the file "trajct.dat" in which a **TRAJCT** bulk data card with ID = 100 and a **TIMESP** bulk data card with ID = 201 are stored. These two bulk data cards are automatically inserted into the bulk data section by the **INCLUDE** bulk data card shown as follows:

INCLUDE trajct.dat

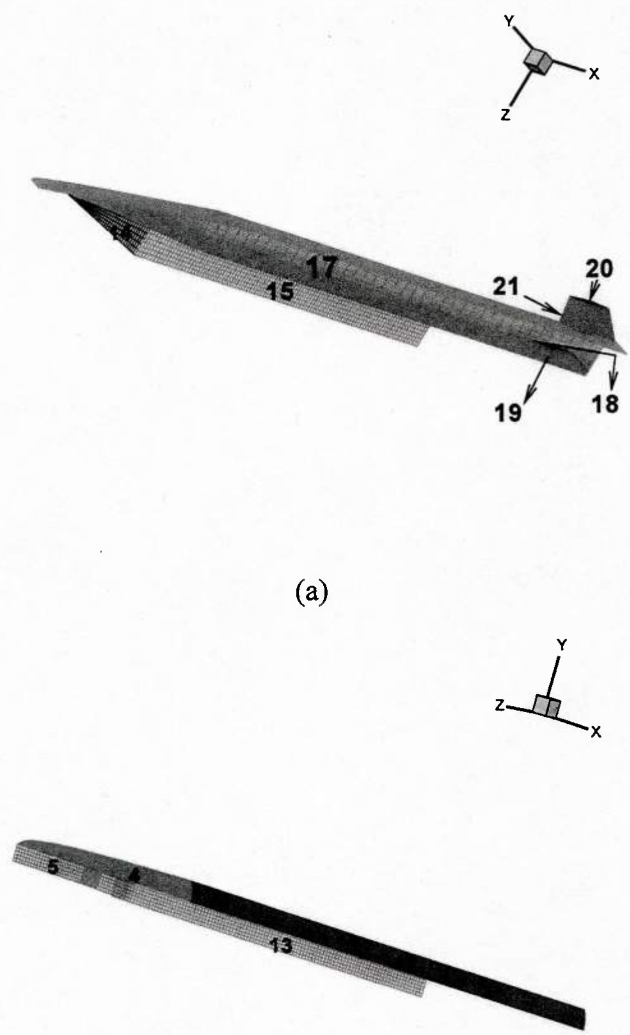
Note that the **TRAJCT** bulk data card with ID = 100 is referred to by a **TRJLST** bulk data card with ID = 1 that is activated by the **TPSDES** bulk data card with ID = 100. The parameters for computing the heat flux by the aeroheating analysis are defined in a **THERMPR** bulk data card with ID = 10 that is referred to by the **TRAJCT** bulk data card with ID = 100.

In order to design the minimum TPS weight on those 7 patches, 7 **TPSSYM** bulk data cards with ID = 400, 500, 1200, 1300, 1400, 1500, 1700, 1800, 1900, 2000, and 2100 are specified that are all referred to by the **TPSDES** bulk data card with ID = 100. Each **TPSSYM** bulk data card refers to a **PRVAL** bulk data card, a **DESVAR** bulk data card, a **PATCH** bulk data card and two **PANLST2** bulk data cards. The **PRVAL** bulk data card with ID = 1001 that is referred to by all the 11 **TPSSYM** bulk data cards defines the parameters for the transient thermal analysis. The **PATCH** bulk data card first refers to a **PANLST2** bulk data card to list the identification numbers of the panels that belong to a patch in the aerodynamic mesh. Then it refers to another **PANLST2** bulk data card to define a set of so-called "hot panels" on which the temperature constraints of the TPS is imposed by listing the identification numbers of those hot panels. Note that those hot panels must be a subset of the panels of the patch.

The temperature constraints are evaluated at all layers of the TPS located on those hot panels and are computed at a set of time steps defined by the **TIMESP** bulk data card with ID = 201. Thus, the total number of the temperature constraints is product of the number of layers of the TPS, the number of the hot panels, and the number of time steps listed in the **TIMESP** bulk data card. This is the reason why only 6 time steps in the **TIMESP** are selected from those 25 time steps in the **TRAJCT** bulk data card. Otherwise, if all those 25 time steps listed in the **TRAJCT** bulk data card are used to evaluate the temperature constraints, the number of temperature constraints would be too many and might require the amount of computer memory beyond the available memory in the computer.

Seven **PATCH** bulk data cards with ID = 401, 501, 1201, 1301, 1401, 1501, 1701, 1801, 1901, 2001, and 2101 that are referred to by those 11 **TPSSYM** bulk data cards respectively, are used to define the panels on those 11 outer surface patches in the aerodynamic mesh by specifying 11 **PANLST2** bulk data cards with ID = 401, 501, 1201, 1301, 1401, 1501, 1701, 1801, 1901, 2001,

and 2101. The hot panels on those 11 patches are defined by another 7 **PANLST2** bulk data cards with ID = 403, 503, 1203, 1303, 1403, 1503, 1703, 1803, 1903, 2003, and 2103. The identification numbers of those panels on the 11 patches are presented in Figure 9.6.3.



(a)

Y
Z
X
5
4
13

(b)

Figure 9.6.3 Panel Identification Numbers on the 11 Patches with TPS

The correspondences between 11 patches and the zones shown in Figure 9.2.1 are:

patch 4: forebody bottom

patch 5: ramp bottom

patch 12: aftbody bottom

patch 13: cowl bottom

patch 14: ramp wall outside

patch 15: combustor wall outside

patch 17: SED body top

patch 18: control surface 1 top

patch 19: control surface 1 bottom

patch 20: control surface 2 top

patch 21: control surface 2 bottom

Patches 4 and 5 with panel ID starting from 400001 and 500001, respectively, are potentially exposed to the high aeroheating environment. This suggests that in order to achieve a minimum weight design of the TPS, different TPS concepts and materials from the rest of the patches be employed for those two patches. This TPS consists of two TPS layers and is defined in the **TPSSYM** bulk data cards with ID = 400 and 500 in which the top layer is defined by a **STTYPE** bulk data card with ID = 31 and the bottom layer is defined by a **STTYPE** bulk data card with ID = 33. The **STTYPE** bulk data card with ID = 31 defines a Slab TPS structure made by ZIRCONIA FIBERS with initial thickness = 0.1 m whereas the STTYPE bulk data card with ID = 33 defines a Slab structure made by a HEAT SINK with thickness = 0.2 m. This HEAT SINK is a virtual material with a very high heat capacity to represent an active cooling concept that absorbs the heat by circling the fuel. The thickness of the ZIRCONIA FIBERS is subjected to the design for minimum weight with the design variable being defined by a **DESVAR** bulk data card whereas the thickness of the HEAT SINK is kept to be constant at 0.2 m. Two **DESVAR** bulk data cards with ID = 400 and 500 are specified that are referred to by the entry DESVAR1 of the **TPSSYM** bulk data cards with ID = 400 and 500, respectively. A minimum and maximum thickness of 0.0002 m and 10.0 m for the ZIRCORNIA FIBERS is also specified in these **TPSSYM** bulk data cards. Note that the entry DESVAR2 of these two **TPSSYM** bulk

data cards is blank to indicate that the bottom layer; i.e. the thickness of the HEAT SINK, is not subjected to design and remains unaltered. The purpose of the **DESVAR** bulk data card is to define a curvilinear coordinates over the patch on which a set of shape functions can be formulated to represent the thickness distribution of the ZIRCONIA FIBERS on this patch. Thus, the actual design variables controlled by the optimizer are the unknown coefficients of those shape functions and are not the thickness of the ZIRCORNIA FIBERS on each panel. Using these shape functions, the number of design variables can be greatly reduced and the thickness distribution of the optimized TPS is ensured to be smooth for the ease of fabrication. This curvilinear coordinates is defined by selecting a set of M by N panels on the patch. A 2 by 2 panels is defines by the **DESVAR** bulk data cards with ID = 400 and a 2 by 3 panels is defined by the **DESVAR** bulk data card with ID = 500. (Please refer to Users Manual Section 5.4, TPSOPT Bulk Data Section, for more information about DESVAR bulk data card.)

The TPS on the rest of 9 patches defined by the four **TPSSYM** bulk data cards with ID = 1200, 1300, 1400, 1500, 1700, 1800, 1900, 2000 and 2100 is also a two-layer TPS. The top layer is a Slab structure made by CRI-II and is defined by a **STTYPE** bulk data card with ID = 11 whereas the bottom layer is a thin skin made by RTV-560 and is defined by a **STTYPE** bulk data card with ID = 21. The top layer is subjected to design with initial thickness of 0.1 m and minimum thickness and maximum thickness of 0.002 m and 10.0 m, respectively, and the bottom layer is kept to be 2.45×10^{-5} m. The **DESVAR** bulk data cards with ID = 1200, 1300, 1400, 1500, 1700, 1800, 1900, 2000 and 2100 that are referred by the **TPSSYM** bulk data cards with ID = 1200, 1300, 1400, 1500, 1700, 1800, 1900, 2000 and 2100, respectively, are specified to select an M by N panels for defining the curvilinear coordinates on their respective patches. A set of 2 by 2 panels is defined by the **DESVAR** bulk data cards with ID = 1700, 1800, 1900, 2000 and 2100 and a set of 3 by 3 panels by the **DESVAR** bulk data card with ID = 1200. The panels set are 3 by 2 and 2 by 3 for **DESVAR** bulk data card with ID = 1300 and 1400 respectively. (Please refer to Users Manual Section 5.4, TPSOPT Bulk Data Section, for more information about DESVAR bulk data card.)

In order to visualize to optimized TPS thickness distribution, two **PLTTPS** bulk data cards with ID = 103 and = -104 are employed that generate two TECPLOT files called "SED_TPS3.PLT"

and "SED_TPS4.PLT", respectively where the first contains the thickness of each TPS layer and the maximum temperature on each panel and the latter contains the total thickness of the TPS. In addition, the heat flux at a time step in the trajectory can be also outputted in a TECPLOT file by specifying a file name in the **TRAJCT** bulk data card. A TECPLOT file called "1283.PLT' is generated to display the heat flux at the last time step of the trajectory.

The final optimized averaged TPS thickness of each layer of patched 400, 500, 1200, 1300, 1400, 1500, 1700, 1800, 1900, 2000 and 2100 are shown in Figures 2.6.4 to 2.6.14. The masses of those 11 TPS are 5.85777017E-03, 4.91326593E-03, 4.33150432E+00, 1.48797294E-01, 3.83791494E-02, 2.14508372E-01, 1.58559431E+01, 6.73263566E-01, 6.52450415E-01, 6.19316060E-01, and 6.61571832E-01 KG, respectively; giving a total mass of the entire TPS of 43.24 KG (both sides). This total mass along with the sum of the product of TPS mass on each panel and the location of the panel is stored in a file called "mass_tps.dat" that is shown in Listing 9.6.3. This file will be an input file of UCDA to include the TPS weight in the total vehicle weight for the next design cycle.

```
                OPTIMAL STRUCTURES OF TPS FOR PATCH =      400
                       (WITH AVERAGE THICKNESS)
============================================================   -----
                                                                 i
                ZIRCONIA FIBERS       slab                     0.00066 FT    1840.8 F
                                                                 i
============================================================   -----
                                                                 i
                HEAT SINK             slab                     0.65617 FT    1771.5 F
                                                                 i
============================================================   -----
```

Figure 9.6.4 Optimized Averaged TPS Thickness of Patch 400

```
                OPTIMAL STRUCTURES OF TPS FOR PATCH =      500
                       (WITH AVERAGE THICKNESS)
============================================================   -----
                                                                 i
                ZIRCONIA FIBERS       slab                     0.00066 FT    2139.8 F
                                                                 i
============================================================   -----
                                                                 i
                HEAT SINK             slab                     0.65617 FT    2069.4 F
                                                                 i
============================================================   -----
```

Figure 9.6.5 Optimized Averaged TPS Thickness of Patch 500

```
             OPTIMAL STRUCTURES OF TPS FOR PATCH =    1200
                    (WITH AVERAGE THICKNESS)
============================================================   -----
                                                                 i
                   CRI-I  2.0           slab                   0.09478 FT   1576.5 F
                                                                 i
============================================================   -----
                   RTV-560              thin skin              0.00066 FT    494.6 F
============================================================   -----
```

Figure 9.6.6 Optimized Averaged TPS Thickness of Patch 1200

```
             OPTIMAL STRUCTURES OF TPS FOR PATCH =    1300
                    (WITH AVERAGE THICKNESS)
============================================================   -----
                                                                 i
                   CRI-I  2.0           slab                   0.00066 FT    100.0 F
                                                                 i
============================================================   -----
                   RTV-560              thin skin              0.00066 FT    100.0 F
============================================================   -----
```

Figure 9.6.7 Optimized Averaged TPS Thickness of Patch 1300

```
             OPTIMAL STRUCTURES OF TPS FOR PATCH =    1400
                    (WITH AVERAGE THICKNESS)
============================================================   -----
                                                                 i
                   CRI-I  2.0           slab                   0.00066 FT    100.0 F
                                                                 i
============================================================   -----
                   RTV-560              thin skin              0.00066 FT    100.0 F
============================================================   -----
```

Figure 9.6.8 Optimized Averaged TPS Thickness of Patch 1400

```
             OPTIMAL STRUCTURES OF TPS FOR PATCH =    1500
                    (WITH AVERAGE THICKNESS)
============================================================   -----
                                                                 i
                   CRI-I  2.0           slab                   0.00066 FT    100.0 F
                                                                 i
============================================================   -----
                   RTV-560              thin skin              0.00066 FT    100.0 F
============================================================   -----
```

Figure 9.6.9 Optimized Averaged TPS Thickness of Patch 1500

```
             OPTIMAL STRUCTURES OF TPS FOR PATCH =    1700
                    (WITH AVERAGE THICKNESS)
============================================================   -----
                                                                 i
                   CRI-I  2.0           slab                   0.07724 FT   2173.7 F
                                                                 i
============================================================   -----
                   RTV-560              thin skin              0.00066 FT    546.2 F
============================================================   -----
```

Figure 9.6.10 Optimized averaged TPS thickness of patch 1700

```
             OPTIMAL STRUCTURES OF TPS FOR PATCH =    1800
                    (WITH AVERAGE THICKNESS)
============================================================   -----
                                                                 i
                   CRI-I  2.0           slab                   0.07815 FT   1962.3 F
                                                                 i
```

```
============================================================    -----
                RTV-560              thin skin             0.00066 FT    546.0 F
============================================================    -----
```

Figure 9.6.11 Optimized averaged TPS thickness of patch 1800

```
             OPTIMAL STRUCTURES OF TPS FOR PATCH =    1900
                    (WITH AVERAGE THICKNESS)
============================================================    -----
                                                              i
                CRI-I  2.0           slab                  0.07589 FT   1962.3 F
                                                              i
============================================================    -----
                RTV-560              thin skin             0.00066 FT    480.3 F
============================================================    -----
```

Figure 9.6.12 Optimized averaged TPS thickness of patch 1900

```
             OPTIMAL STRUCTURES OF TPS FOR PATCH =    2000
                    (WITH AVERAGE THICKNESS)
============================================================    -----
                                                              i
                CRI-I  2.0           slab                  0.07154 FT   1922.1 F
                                                              i
============================================================    -----
                RTV-560              thin skin             0.00066 FT    533.8 F
============================================================    -----
```

Figure 9.6.13 Optimized averaged TPS thickness of patch 2000

```
             OPTIMAL STRUCTURES OF TPS FOR PATCH =    2100
                    (WITH AVERAGE THICKNESS)
============================================================    -----
                                                              i
                CRI-I  2.0           slab                  0.07714 FT   1922.0 F
                                                              i
============================================================    -----
                RTV-560              thin skin             0.00066 FT    509.1 F
============================================================    -----
```

Figure 9.6.14 Optimized averaged TPS thickness of patch 2100

Using the file "SED_TPS4.PLT", the total thickness contour of the TPS and the maximum temperature distribution are depicted in Figures 9.6.15 and 9.6.16, respectively. The heat flux at the last time step of the trajectory is shown in Figure 9.6.17.

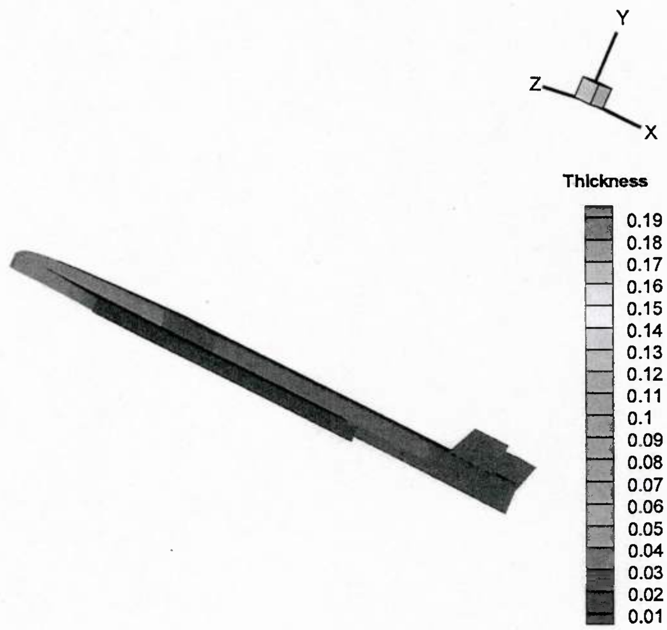


Figure 9.6.15 Thickness Contour of the Optimized TPS

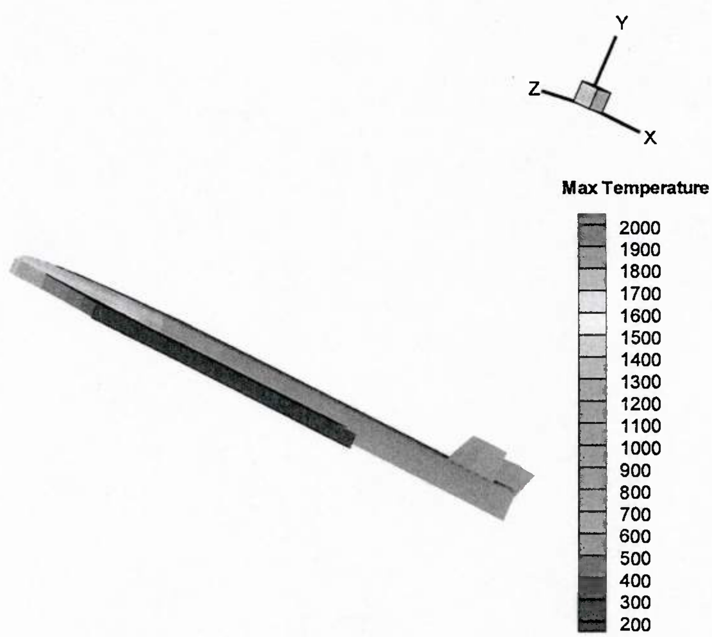


Figure 9.6.16 Temperature Contour of the Optimized TPS

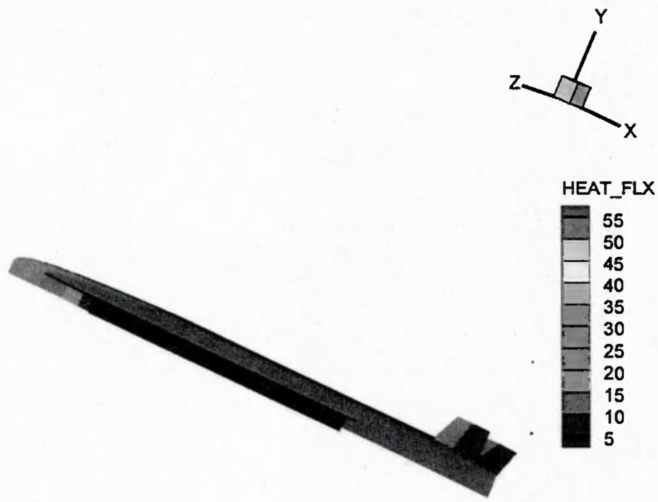


Figure 1.6.17 Heat Flux at the Last Time Step of the Trajectory

Listing 9.6.1 Sample Input File: sed_tpsopt.inp

```
ASSIGN AEROBASE=geom_data.DAT,print=1

CEND

TITLE=SED

ECHO=SORT

SUBCASE =1

   TPSDES=100

BEGIN BULK

INCLUDE 'trajct.dat'

$2345678123456781234567812345678123456781234567812345678123456781234567812345678

PLTAERO 1                             tecplot aero.plt

PLTAERO 2                             nastran aerol.plt

$...1..|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|...10..|

$          SETID  TPSDES  TPSSYM    FORM     FILENM

PLTTPS       103     100      ALL TECPLOT   SED_TPS3.PLT  -30.00

PLTTPS      -104     100      ALL TECPLOT   SED_TPS4.PLT  -30.00

TPSDES  100      1       1

        400     500     1200    1300     1400    1500    1700    1800
```

```
        1900    2000    2100
TRJLST  1
        100
THERMPR 10      100.F   yes     2       0       0.8
$234567812345678123456781234567812345678123456781234567812345678123456781234567812345678
$forebody bottom
TPSSYM  400     401     2       1001
        400     31      .0002   10.
                33      .0002   10.
PATCH   401     401     403     NO              201
PANLST2 401     400001  400001  thru    400900
PANLST2 403     400001  400001  400030  400871  400900
DESVAR  400     2       2
        400001  400030
        400871  400900
$234567812345678123456781234567812345678123456781234567812345678123456781234567812345678
$ramp bottom
TPSSYM  500     501     2       1001
        500     31      .0002   10.
                33      .0002   10.
PATCH   501     501     503     NO              201
PANLST2 501     500001  500001  thru    500270
PANLST2 503     500001  500001  500054  500109  500162  500217  500270
DESVAR  500     2       3
        500001  500054
        500109  500162
        500217  500270
$234567812345678123456781234567812345678123456781234567812345678123456781234567812345678
$aftbody bottom
TPSSYM  1200    1201    2       1001
        1200    11      .0002   10.
                21      .0002   10.
PATCH   1201    1201    1203    NO              201
PANLST2 1201    1200001 1200001 thru    1203000
PANLST2 1203    1200001 1200001 1200025 1200050 1200075 1200100 1201501
        1201525 1201550 1201575 1201600 1202901 1202925 1202950 1202975
```

```
        1203000
DESVAR  1200    3       3
        1200001 1201501 1202901
        1200050 1201550 1202950
        1200100 1201600 1203000
$2345678123456781234567812345678123456781234567812345678123456781234567812345678
$cowl bottom
TPSSYM  1300    1301    2       1001
        1300    11      .0002   10.
                21      .0002   10.
PATCH   1301    1301    1303    NO              201
PANLST2 1301    1300001 1300001 thru    1300500
PANLST2 1303    1300001 1300001 1300050 1300100 1300401 1300450 1300500
DESVAR  1300    3       2
        1300001 1300050 1300100
        1300401 1300450 1300500
$2345678123456781234567812345678123456781234567812345678123456781234567812345678
$ramp wall outside
TPSSYM  1400    1401    2       1001
        1400    11      .0002   10.
                21      .0002   10.
PATCH   1401    1401    1403    NO              201
PANLST2 1401    1400001 1400001 thru    1400170
PANLST2 1403    1400001 1400001 1400017 1400034 1400137 1400153 1400170
DESVAR  1400    2       3
        1400001 1400137
        1400017 1400153
        1400034 1400170
$2345678123456781234567812345678123456781234567812345678123456781234567812345678
$combustor wall outside
TPSSYM  1500    1501    2       1001
        1500    11      .0002   10.
                21      .0002   10.
PATCH   1501    1501    1503    NO              201
PANLST2 1501    1500001 1500001 thru    1500600
PANLST2 1503    1500001 1500001 1500050 1500100 1500501 1500550 1500600
```

```
DESVAR  1500    3       2
        1500001 1500050 1500100
        1500501 1500550 1500600
$2345678123456781234567812345678123456781234567812345678123456781234567812345678
$nozzle wall outside
TPSSYM  1600    1601    2       1001
        1600    11      .0002   10.
                21      .0002   10.
PATCH   1601    1601    1603    NO              201
PANLST2 1601    1600001 1600001 thru    1600600
PANLST2 1603    1600001 1600001 1600020 1600101 1600120
DESVAR  1600    2       2
        1600001 1600020
        1600101 1600120
$2345678123456781234567812345678123456781234567812345678123456781234567812345678
$SED body
TPSSYM  1700    1701    2       1001
        1700    11      .0002   10.
                21      .0002   10.
$        1700    41      .0002   10.
$        1700    31      .0002   10.
$                31      .0002   10.
PATCH   1701    1701    1703    NO              201
PANLST2 1701    1700001 1700001 thru    1705400
PANLST2 1703    1700001 1700001 1700120 1705281  1705400
DESVAR  1700     2       2
        1700001 1700120
        1705281 1705400
$2345678123456781234567812345678123456781234567812345678123456781234567812345678
$control surface 1 top
TPSSYM  1800    1801    2       1001
        1800    11      .0002   10.
                21      .0002   10.
PATCH   1801    1801    1803    NO              201
PANLST2 1801    1800001 1800001 thru    1800900
PANLST2 1803    1800001 1800001 1800030 1800871 1800900
```

```
DESVAR  1800    2       2
        1800001 1800030
        1800871 1800900
$234567812345678123456781234567812345678123456781234567812345678123456781234567812345678
$control surface 1 bottom
TPSSYM  1900    1901    2       1001
        1900    11      .0002   10.
                21      .0002   10.
PATCH   1901    1901    1903    NO              201
PANLST2 1901    1900001 1900001 thru    1900900
PANLST2 1903    1900001 1900001 1900030 1900871 1900900
DESVAR  1900    2       2
        1900001 1900030
        1900871 1900900
$234567812345678123456781234567812345678123456781234567812345678123456781234567812345678
$control surface 2 top
TPSSYM  2000    2001    2       1001
        2000    11      .0002   10.
                21      .0002   10.
PATCH   2001    2001    2003    NO              201
PANLST2 2001    2000001 2000001 thru    2000900
PANLST2 2003    2000001 2000001 2000030 2000871 2000900
DESVAR  2000    2       2
        2000001 2000030
        2000871 2000900
$234567812345678123456781234567812345678123456781234567812345678123456781234567812345678
$control surface 2 bottom
TPSSYM  2100    2101    2       1001
        2100    11      .0002   10.
                21      .0002   10.
PATCH   2101    2101    2103    NO              201
PANLST2 2101    2100001 2100001 thru    2100900
PANLST2 2103    2100001 2100001 2100030 2100871 2100900
DESVAR  2100    2       2
        2100001 2100030
        2100871 2100900
```

```
$234567812345678123456781234567812345678123456781234567812345678123456781234567812345678
$...1..|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|...10..|
PRVAL       1001        99999000
                                        0
STTYPE  11      1       315
        0.100
STTYPE  21      6       245
        2.45e-5
STTYPE  31      1       251
        0.100
sttype  33      1       701
        0.200
STTYPE  41      1       129
        0.100
$STTYPE  41      1       206
$        0.100
STTYPE  2       1       266
        0.001
STTYPE  3       1       260
        0.001
STTYPE  4       1       266
        0.001
STTYPE  5       1       245
        0.001
STTYPE  6       1       101
        0.010
$234567812345678123456781234567812345678123456781234567812345678123456781234567812345678
ENDDATA
```

Listing 9.6.2 Sample Output File: sed_tpsopt.out

OF ZONA TECHNOLOGY, INC.

E X E C U T I V E   C O N T R O L   S U M M A R Y

```
|...1...|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|..10...|

ASSIGN AEROBASE=geom_data.DAT,print=1
CEND
```

C A S E   C O N T R O L   S U M M A R Y

S I N G L E   P R E C I S I O N   C O M P U T A T I O N

M A X I M U M   A L L O C A B L E   M E M O R Y = 800 M E G A B Y T E S

```
|...1...|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|..10...|

TITLE=SED
ECHO=SORT
SUBCASE =1
TPSDES=100
BEGIN BULK
```

S O R T E D   B U L K   D A T A   E C H O

CARD

```
COUNT        |...1...|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|..10...|

        DESVAR  400     2       2
                400001  400030
                400871  400900
        DESVAR  500     2       3
                500001  500054
                500109  500162
                500217  500270
        DESVAR  1200    3       3
                1200001 1201501 1202901
                1200050 1201550 1202950
                1200100 1201600 1203000
        DESVAR  1300    3       2
                1300001 1300050 1300100
                1300401 1300450 1300500
        DESVAR  1400    2       3
                1400001 1400137
                1400017 1400153
                1400034 1400170
        DESVAR  1500    3       2
                1500001 1500050 1500100
                1500501 1500550 1500600
        DESVAR  1600    2       2
                1600001 1600020
                1600101 1600120
        DESVAR  1700    2       2
                1700001 1700120
                1705281 1705400
        DESVAR  1800    2       2
                1800001 1800030
                1800871 1800900
        DESVAR  1900    2       2
                1900001 1900030
                1900871 1900900
```

```
DESVAR  2000    2       2
        2000001 2000030
        2000871 2000900
DESVAR  2100    2       2
        2100001 2100030
        2100871 2100900
PANLST2 401     400001  400001  THRU    400900
PANLST2 403     400001  400001  400030  400871  400900
PANLST2 501     500001  500001  THRU    500270
PANLST2 503     500001  500001  500054  500109  500162  500217  500270
PANLST2 1201    1200001 1200001 THRU    1203000
PANLST2 1203    1200001 1200001 1200025 1200050 1200075 1200100 1201501
        1201525 1201550 1201575 1201600 1202901 1202925 1202950 1202975
        1203000
PANLST2 1301    1300001 1300001 THRU    1300500
PANLST2 1303    1300001 1300001 1300050 1300100 1300401 1300450 1300500
PANLST2 1401    1400001 1400001 THRU    1400170
PANLST2 1403    1400001 1400001 1400017 1400034 1400137 1400153 1400170
PANLST2 1501    1500001 1500001 THRU    1500600
PANLST2 1503    1500001 1500001 1500050 1500100 1500501 1500550 1500600
PANLST2 1601    1600001 1600001 THRU    1600600
PANLST2 1603    1600001 1600001 1600020 1600101 1600120
PANLST2 1701    1700001 1700001 THRU    1705400
PANLST2 1703    1700001 1700001 1700120 1705281 1705400
PANLST2 1801    1800001 1800001 THRU    1800900
PANLST2 1803    1800001 1800001 1800030 1800871 1800900
PANLST2 1901    1900001 1900001 THRU    1900900
PANLST2 1903    1900001 1900001 1900030 1900871 1900900
PANLST2 2001    2000001 2000001 THRU    2000900
PANLST2 2003    2000001 2000001 2000030 2000871 2000900
PANLST2 2101    2100001 2100001 THRU    2100900
PANLST2 2103    2100001 2100001 2100030 2100871 2100900
PATCH   401     401     403     NO              201
PATCH   501     501     503     NO              201
PATCH   1201    1201    1203    NO              201
PATCH   1301    1301    1303    NO              201
```

```
PATCH    1401    1401    1403    NO              201
PATCH    1501    1501    1503    NO              201
PATCH    1601    1601    1603    NO              201
PATCH    1701    1701    1703    NO              201
PATCH    1801    1801    1803    NO              201
PATCH    1901    1901    1903    NO              201
PATCH    2001    2001    2003    NO              201
PATCH    2101    2101    2103    NO              201
PLTAERO  1                               TECPLOT AERO.PLT
PLTAERO  2                               NASTRAN AERO1.PLT
PLTTPS   -104    100     ALL     TECPLOT SED_T   PS4.PLT -30.00
PLTTPS   103     100     ALL     TECPLOT SED_T   PS3.PLT -30.00
PRVAL    1001            99999000
                                 0
STTYPE   2       1       266
         0.001
STTYPE   3       1       260
         0.001
STTYPE   4       1       266
         0.001
STTYPE   5       1       245
         0.001
STTYPE   6       1       101
         0.010
STTYPE   11      1       315
         0.100
STTYPE   21      6       245
         2.45E-5
STTYPE   31      1       251
         0.100
STTYPE   33      1       701
         0.200
STTYPE   41      1       129
         0.100
THERMPR  10      100.F   YES     2       0       0.8
TIMESP   201     0.000   60.000  120.000 180.000 240.000 282.000
```

```
TPSDES  100   1     1
        400   500   1200  1300  1400  1500  1700  1800
        1900  2000  2100
TPSSYM  400   401   2     1001
        400   31    .0002 10.
              33    .0002 10.
TPSSYM  500   501   2     1001
        500   31    .0002 10.
              33    .0002 10.
TPSSYM  1200  1201  2     1001
        1200  11    .0002 10.
              21    .0002 10.
TPSSYM  1300  1301  2     1001
        1300  11    .0002 10.
              21    .0002 10.
TPSSYM  1400  1401  2     1001
        1400  11    .0002 10.
              21    .0002 10.
TPSSYM  1500  1501  2     1001
        1500  11    .0002 10.
              21    .0002 10.
TPSSYM  1600  1601  2     1001
        1600  11    .0002 10.
              21    .0002 10.
TPSSYM  1700  1701  2     1001
        1700  11    .0002 10.
              21    .0002 10.
TPSSYM  1800  1801  2     1001
        1800  11    .0002 10.
              21    .0002 10.
TPSSYM  1900  1901  2     1001
        1900  11    .0002 10.
              21    .0002 10.
TPSSYM  2000  2001  2     1001
        2000  11    .0002 10.
              21    .0002 10.
```

```
    TPSSYM 2100   2101   2      1001
           2100   11     .0002  10.
                  21     .0002  10.
    TRAJCT 100    10
           0.0    6.9200 26105. -0.110
           12.0   6.9300 26068. -0.130
           24.0   6.9400 25964. -0.150
           36.0   6.9600 25815. -0.160
           48.0   6.9700 25651. -0.180
           60.0   6.9900 25507. -0.200
           72.0   7.0100 25414. -0.210
           84.0   7.0200 25395. -0.230
           96.0   7.0300 25456. -0.250
           108.0  7.0400 25590. -0.260
           120.0  7.0500 25778. -0.280
           132.0  7.0600 25990. -0.300
           144.0  7.0700 26191. -0.310
           156.0  7.0700 26347. -0.330
           168.0  7.0800 26430. -0.350
           180.0  7.0900 26425. -0.360
           192.0  7.1000 26335. -0.380
           204.0  7.1200 26181. -0.400
           216.0  7.1500 26001. -0.410
           228.0  7.1900 25850. -0.430
           240.0  7.2300 25789. -0.450
           252.0  7.2900 25878. -0.460
           264.0  7.3500 26167. -0.480
           276.0  7.4300 26694. -0.500
           282.0  7.4700 27056. -0.510        TECPLOT        1283.PLT
    TRJLST 1
           100
    ENDDATA
```

```
                    ***************************************
                    *                                     *
                    *       SUBCASE        =        1     *
                    *       DISCIPLINE     = TPSDES       *
                    *       BULK ENTRY ID =       100     *
                    *                                     *
                    ***************************************


          OPTIMIZATION SYSTEM FOR TPSSYM =   400


TOTAL NUMBER OF DESIGN VARIABLES =     4

 TOTAL NUMBER OF CONSTRAINS        = 1840

 TOTAL NUMBER OF TEMP. CONSTRAINS =   48

 TOTAL NUMBER OF TEMP. PRINTOUTS  =    6



MAXIMUM TEMPERATURE OF EACH LAYER VS OUTPUT TIMES

    X   0.1841E+04

   1.0 B                      A
       |                      B                      B                      B                      A
       |                                                                                           B
       |
       |
       |
       |
       |
       |
       |
   0.0 +-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+
       |
       |
       |
       |
       |
```

```
      |

      |

      |

      |

-1.0 +

      .00       .10       .20       .30       .40       .50       .60       .70       .80       .90      1.00

                                                    TIME   ( X 2.350E+02 )
```

```
            MAXIMUM TEMPERATURE OF EVERY LAYER

LAYER:        1        2

Tmax:   3000.33  8540.33

Optv:   1840.80  1771.48


                 VALUES OF DESIGN VARIABLES :

LAYER    DEV01    DEV02    DEV03    DEV04

   1  0.00020  0.00020  0.00020  0.00020


 THE ORIGINAL OBJECTIVE FUNCTION =     1771.6535645


 THE RATIO OF OPTIMAL OBJECTIVE FUNCTION =   0.0020000


 THE TOTAL OPTIMAL WEIGHT = 5.85777017E-03


              OPTIMAL STRUCTURES OF TPS FOR PATCH =     400

                   (WITH AVERAGE THICKNESS)

 ============================================================   -----

                                                                  i

                      ZIRCONIA FIBERS      slab                 0.00066 FT   1840.8 F

                                                                  i

 ============================================================   -----

                                                                  i

                      HEAT SINK            slab                 0.65617 FT   1771.5 F

                                                                  i

 ============================================================   -----
```

THICKNESS AND TEMPERATURE OF LAYERS FOR PATCH = 400

PANEL	LAYER01		LAYER02	
400001	0.00020	1840.80	0.20000	1771.48
400002	0.00020	1831.34	0.20000	1796.52
400003	0.00020	1821.88	0.20000	1786.89
400004	0.00020	1812.41	0.20000	1777.27
400005	0.00020	1802.95	0.20000	1767.64..
....				
....				
400895	0.00020	1585.67	0.20000	1546.87
400896	0.00020	1585.67	0.20000	1546.87
400897	0.00020	1374.48	0.20000	1332.51
400898	0.00020	1366.32	0.20000	1324.23
400899	0.00020	1358.16	0.20000	1315.96
400900	0.00020	1350.01	0.20000	1265.35

OPTIMIZATION SYSTEM FOR TPSSYM = 500

TOTAL NUMBER OF DESIGN VARIABLES = 6

TOTAL NUMBER OF CONSTRAINS = 600

TOTAL NUMBER OF TEMP. CONSTRAINS = 72

TOTAL NUMBER OF TEMP. PRINTOUTS = 6

MAXIMUM TEMPERATURE OF EACH LAYER VS OUTPUT TIMES

```
   X   0.2140E+04
 1.0 B                     A
     |                     B                     B                     B                     A
     |                                                                                       B
     |
     |
     |
     |
```

```
          |
          |
          |
    0.0 +-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+
          |
          |
          |
          |
          |
          |
          |
          |
          |
   -1.0 +
         .00        .10        .20        .30        .40        .50        .60        .70        .80        .90       1.00
                                                     TIME  ( X 2.350E+02 )
```

```
             MAXIMUM TEMPERATURE OF EVERY LAYER

LAYER:         1         2

Tmax:    3000.33   8540.33

Optv:    2139.84   2069.40


                  VALUES OF DESIGN VARIABLES :

LAYER    DEV01     DEV02     DEV03     DEV04     DEV05     DEV06

    1  0.00020   0.00020   0.00020   0.00020   0.00020   0.00020


 THE ORIGINAL OBJECTIVE FUNCTION =      531.4960938


 THE RATIO OF OPTIMAL OBJECTIVE FUNCTION =    0.0020000


 THE TOTAL OPTIMAL WEIGHT = 4.91326593E-03


             OPTIMAL STRUCTURES OF TPS FOR PATCH =      500

                    (WITH AVERAGE THICKNESS)

 ============================================================   -----
```

i

ZIRCONIA FIBERS   slab   0.00066 FT   2139.8 F

i

==   -----

i

HEAT SINK   slab   0.65617 FT   2069.4 F

i

==   -----

THICKNESS AND TEMPERATURE OF LAYERS FOR PATCH =   500

PANEL	LAYER01		LAYER02	
500001	0.00020	1713.02	0.20000	1676.61
500002	0.00020	1722.32	0.20000	1685.94
500003	0.00020	1731.62	0.20000	1695.26
500004	0.00020	1740.92	0.20000	1704.59
500005	0.00020	1750.22	0.20000	1713.91..
....				
....				
500266	0.00020	2090.93	0.20000	2055.58
500267	0.00020	2103.16	0.20000	2067.84
500268	0.00020	2115.39	0.20000	2080.10
500269	0.00020	2127.62	0.20000	2092.36
500270	0.00020	2139.84	0.20000	2104.62

OPTIMIZATION SYSTEM FOR TPSSYM = 1200

TOTAL NUMBER OF DESIGN VARIABLES =   9

TOTAL NUMBER OF CONSTRAINS   = 6162

TOTAL NUMBER OF TEMP. CONSTRAINS = 180

TOTAL NUMBER OF TEMP. PRINTOUTS =   6

WARNING: MODIFICATION EXEEDS ALLOWED VALUE

WARNING: MODIFICATION EXEEDS ALLOWED VALUE

WARNING: MODIFICATION EXEEDS ALLOWED VALUE

WARNING: MODIFICATION EXEEDS ALLOWED VALUE

WARNING: MODIFICATION EXEEDS ALLOWED VALUE

MAXIMUM TEMPERATURE OF EACH LAYER VS OUTPUT TIMES

```
    X   0.1576E+04

  1.0 A                   A                   A                   A                   A
      |
      |
      |
      |
      |
      |
      B
      |                   B                   B
      |                                                           B                   B
  0.0 +---------+---------+---------+---------+---------+---------+---------+---------+---------+---------+
      |
      |
      |
      |
      |
      |
      |
      |
      |
 -1.0 +
     .00       .10       .20       .30       .40       .50       .60       .70       .80       .90      1.00

                                          TIME  ( X 2.350E+02 )
```

MAXIMUM TEMPERATURE OF EVERY LAYER

LAYER:	1	2
Tmax:	2400.33	550.33
Optv:	1576.49	494.62

VALUES OF DESIGN VARIABLES :

LAYER	DEV01	DEV02	DEV03	DEV04	DEV05	DEV06	DEV07	DEV08	DEV09
1	0.02205	0.02222	0.02235	0.03637	0.03652	0.03639	0.02058	0.02062	0.02064

THE ORIGINAL OBJECTIVE FUNCTION = 10452.7558594

THE RATIO OF OPTIMAL OBJECTIVE FUNCTION = 0.3134504

THE TOTAL OPTIMAL WEIGHT = 4.33150432E+00

OPTIMAL STRUCTURES OF TPS FOR PATCH = 1200

(WITH AVERAGE THICKNESS)

== -----

i

CRI-I 2.0 slab 0.09478 FT 1576.5 F

i

== -----

RTV-560 thin skin 0.00066 FT 494.6 F

== -----

THICKNESS AND TEMPERATURE OF LAYERS FOR PATCH = 1200

PANEL	LAYER01		LAYER02	
1200001	0.02205	1576.34	0.00002	550.33
1200002	0.02264	1575.26	0.00002	550.33
1200003	0.02322	1574.19	0.00002	550.33
1200004	0.02378	1573.12	0.00002	550.33
1200005	0.02433	1572.07	0.00002	550.33..

....

....

1202995	0.02358	1510.20	0.00002	550.33
1202996	0.02302	1509.88	0.00002	550.33
1202997	0.02244	1509.57	0.00002	550.33
1202998	0.02185	1509.27	0.00002	550.33
1202999	0.02125	1508.98	0.00002	550.33
1203000	0.02064	1508.69	0.00002	550.33

OPTIMIZATION SYSTEM FOR TPSSYM = 1300

```
TOTAL NUMBER OF DESIGN VARIABLES =    6
TOTAL NUMBER OF CONSTRAINS       = 1060
TOTAL NUMBER OF TEMP. CONSTRAINS =   72
TOTAL NUMBER OF TEMP. PRINTOUTS  =    6
```

```
MAXIMUM TEMPERATURE OF EACH LAYER VS OUTPUT TIMES
    X   0.1000E+03
   1.0 B
       I
       I
       I
       I
       I                      B
       I
       I                                              B
       I                                                                      B
       I                                                                      A                      B
   0.0 +-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+
       I
       I
       I
       I
       I
       I
       I
       I
  -1.0 +
       .00         .10         .20         .30         .40         .50         .60         .70         .80         .90
  1.00
                                                        TIME  ( X 2.350E+02 )
```

MAXIMUM TEMPERATURE OF EVERY LAYER

LAYER:	1	2
Tmax:	2400.33	550.33
Optv:	100.00	100.00

VALUES OF DESIGN VARIABLES :

LAYER	DEV01	DEV02	DEV03	DEV04	DEV05	DEV06
1	0.00020	0.00020	0.00020	0.00020	0.00020	0.00020

THE ORIGINAL OBJECTIVE FUNCTION = 1742.1259766

THE RATIO OF OPTIMAL OBJECTIVE FUNCTION = 0.0020000

THE TOTAL OPTIMAL WEIGHT = 1.48797294E-01

```
               OPTIMAL STRUCTURES OF TPS FOR PATCH =    1300
                      (WITH AVERAGE THICKNESS)
==========================================================   -----
                                                              i
                     CRI-I  2.0          slab              0.00066 FT    100.0 F
                                                              i
==========================================================   -----
                     RTV-560             thin skin         0.00066 FT    100.0 F
==========================================================   -----
```

THICKNESS AND TEMPERATURE OF LAYERS FOR PATCH = 1300

PANEL	LAYER01		LAYER02	
1300001	0.00020	100.00	0.00002	100.00
1300002	0.00020	100.00	0.00002	100.00
1300003	0.00020	100.00	0.00002	100.00
1300004	0.00020	100.00	0.00002	100.00
1300005	0.00020	100.00	0.00002	100.00

....

....

1300495	0.00020	100.00	0.00002	100.00
1300496	0.00020	100.00	0.00002	100.00
1300497	0.00020	100.00	0.00002	100.00
1300498	0.00020	100.00	0.00002	100.00
1300499	0.00020	100.00	0.00002	100.00
1300500	0.00020	100.00	0.00002	100.00

OPTIMIZATION SYSTEM FOR TPSSYM = 1400

```
TOTAL NUMBER OF DESIGN VARIABLES =    6
TOTAL NUMBER OF CONSTRAINS       =  400
TOTAL NUMBER OF TEMP. CONSTRAINS =   72
TOTAL NUMBER OF TEMP. PRINTOUTS  =    6
```

```
MAXIMUM TEMPERATURE OF EACH LAYER VS OUTPUT TIMES
    X    0.1000E+03
   1.0 B
       I
       I
       I
       I
       I                      B
      .I
       I                                  B
       I
       I                                              B                   B
   0.0 +-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+
       I
       I
       I
       I
       I
       I
       I
       I
  -1.0 +
      .00         .10         .20         .30         .40         .50         .60         .70         .80         .90
  1.00
                                                  TIME  ( X 2.350E+02 )
```

MAXIMUM TEMPERATURE OF EVERY LAYER

LAYER:	1	2
Tmax:	2400.33	550.33
Optv:	100.00	100.00

VALUES OF DESIGN VARIABLES :

LAYER	DEV01	DEV02	DEV03	DEV04	DEV05	DEV06
1	0.00020	0.00020	0.00020	0.00020	0.00020	0.00020

THE ORIGINAL OBJECTIVE FUNCTION = 592.3228149

THE RATIO OF OPTIMAL OBJECTIVE FUNCTION = 0.0020000

THE TOTAL OPTIMAL WEIGHT = 3.83791494E-02

OPTIMAL STRUCTURES OF TPS FOR PATCH = 1400
(WITH AVERAGE THICKNESS)

```
==========================================================   -----
                                                               i
                    CRI-I  2.0           slab                0.00066 FT    100.0 F
                                                               i
==========================================================   -----
                    RTV-560              thin skin           0.00066 FT    100.0 F
==========================================================   -----
```

THICKNESS AND TEMPERATURE OF LAYERS FOR PATCH = 1400

PANEL	LAYER01		LAYER02	
1400001	0.00020	100.00	0.00002	100.00
1400002	0.00020	100.00	0.00002	100.00
1400003	0.00020	100.00	0.00002	100.00
1400004	0.00020	100.00	0.00002	100.00
1400005	0.00020	100.00	0.00002	100.00

....

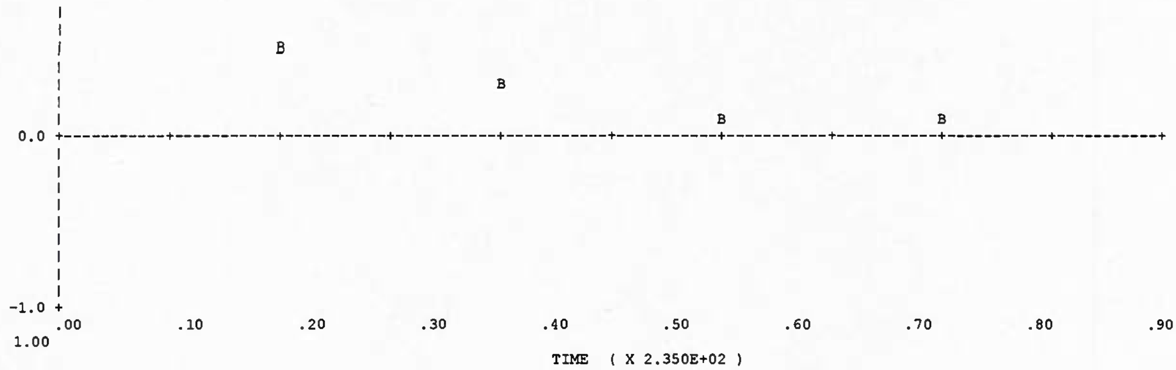
....

1400166	0.00020	100.00	0.00002	100.00
1400167	0.00020	100.00	0.00002	100.00
1400168	0.00020	100.00	0.00002	100.00
1400169	0.00020	100.00	0.00002	100.00
1400170	0.00020	100.00	0.00002	100.00

OPTIMIZATION SYSTEM FOR TPSSYM = 1500

```
TOTAL NUMBER OF DESIGN VARIABLES =    6
TOTAL NUMBER OF CONSTRAINS       = 1260
TOTAL NUMBER OF TEMP. CONSTRAINS =   72
TOTAL NUMBER OF TEMP. PRINTOUTS  =    6
```

```
MAXIMUM TEMPERATURE OF EACH LAYER VS OUTPUT TIMES
    X    0.1000E+03
   1.0 B
       I
       I
```



MAXIMUM TEMPERATURE OF EVERY LAYER

LAYER:	1	2
Tmax:	2400.33	550.33
Optv:	100.00	100.00

VALUES OF DESIGN VARIABLES :

LAYER	DEV01	DEV02	DEV03	DEV04	DEV05	DEV06
1	0.00020	0.00020	0.00020	0.00020	0.00020	0.00020

THE ORIGINAL OBJECTIVE FUNCTION = 2090.5512695

THE RATIO OF OPTIMAL OBJECTIVE FUNCTION = 0.0020000

THE TOTAL OPTIMAL WEIGHT = 2.14508372E-01

OPTIMAL STRUCTURES OF TPS FOR PATCH = 1500
(WITH AVERAGE THICKNESS)

CRI-I 2.0	slab	0.00066 FT	100.0 F	i
RTV-560	thin skin	0.00066 FT	100.0 F	

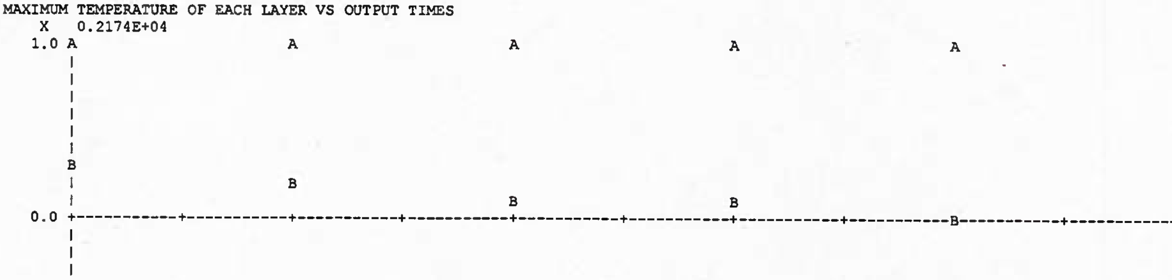
THICKNESS AND TEMPERATURE OF LAYERS FOR PATCH = 1500

PANEL	LAYER01		LAYER02	
1500001	0.00020	100.00	0.00002	100.00
1500002	0.00020	100.00	0.00002	100.00
1500003	0.00020	100.00	0.00002	100.00
1500004	0.00020	100.00	0.00002	100.00
1500005	0.00020	100.00	0.00002	100.00
....				
....				
1500595	0.00020	100.00	0.00002	100.00
1500596	0.00020	100.00	0.00002	100.00
1500597	0.00020	100.00	0.00002	100.00
1500598	0.00020	100.00	0.00002	100.00
1500599	0.00020	100.00	0.00002	100.00
1500600	0.00020	100.00	0.00002	100.00

OPTIMIZATION SYSTEM FOR TPSSYM = 1700

TOTAL NUMBER OF DESIGN VARIABLES = 4
TOTAL NUMBER OF CONSTRAINS =10840
TOTAL NUMBER OF TEMP. CONSTRAINS = 48
TOTAL NUMBER OF TEMP. PRINTOUTS = 6

MAXIMUM TEMPERATURE OF EACH LAYER VS OUTPUT TIMES



```
       |
       |
       |
       |
       |
 -1.0 +
       .00        .10        .20        .30        .40        .50        .60        .70        .80        .90
  1.00
                                                            TIME  ( X 2.350E+02 )
```

```
                MAXIMUM TEMPERATURE OF EVERY LAYER
LAYER:          1          2
Tmax:    2400.33    550.33
Optv:    2173.75    546.23

                     VALUES OF DESIGN VARIABLES :
LAYER    DEV01    DEV02    DEV03    DEV04
    1  0.02657  0.02222  0.02324  0.02214

 THE ORIGINAL OBJECTIVE FUNCTION =    18814.9609375

 THE RATIO OF OPTIMAL OBJECTIVE FUNCTION =    0.2420817

 THE TOTAL OPTIMAL WEIGHT = 1.58559431E+01

                OPTIMAL STRUCTURES OF TPS FOR PATCH =     1700
                       (WITH AVERAGE THICKNESS)
 ==============================================================   -----
                                                                    i
                      CRI-I  2.0           slab                   0.07724 FT    2173.7 F
                                                                    i
 ==============================================================   -----
                      RTV-560              thin skin              0.00066 FT     546.2 F
 ==============================================================   -----
```

```
          THICKNESS AND TEMPERATURE OF LAYERS FOR PATCH =     1700

   PANEL    LAYER01              LAYER02
 1700001    0.02657    2173.75    0.00002    550.33
 1700002    0.02657    2173.51    0.00002    550.33
 1700003    0.02656    2173.25    0.00002    550.33
 1700004    0.02656    2173.00    0.00002    550.33
 1700005    0.02656    2172.75    0.00002    550.33
.................................................................

.................................................................

1705395    0.02224    1618.14    0.00002    550.33
 1705396    0.02222    1613.83    0.00002    550.33
 1705397    0.02220    1609.53    0.00002    550.33
 1705398    0.02218    1605.23    0.00002    550.33
 1705399    0.02216    1600.93    0.00002    550.33
 1705400    0.02214    1596.62    0.00002    550.33
```

```
                     OPTIMIZATION SYSTEM FOR TPSSYM =  1800

 TOTAL NUMBER OF DESIGN VARIABLES =     4
 TOTAL NUMBER OF CONSTRAINS        = 1840
 TOTAL NUMBER OF TEMP. CONSTRAINS =   48
 TOTAL NUMBER OF TEMP. PRINTOUTS  =    6
 WARNING: MODIFICATION EXEEDS ALLOWED VALUE

 WARNING: MODIFICATION EXEEDS ALLOWED VALUE
```

```
MAXIMUM TEMPERATURE OF EACH LAYER VS OUTPUT TIMES
    X    0.1962E+04
  1.0 A                        A                        A                        A                        A
      |
      |
      |
      |
      |
      |
      B
      |                        B
      |                                                 B                        B                        B
  0.0 +-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+
      |
      |
      |
      |
      |
      |
      |
      |
 -1.0 +
       .00        .10        .20        .30        .40        .50        .60        .70        .80        .90
  1.00
```

TIME (X 2.350E+02)

MAXIMUM TEMPERATURE OF EVERY LAYER

LAYER:	1	2
Tmax:	2400.33	550.33
Optv:	1962.31	546.03

VALUES OF DESIGN VARIABLES :

LAYER	DEV01	DEV02	DEV03	DEV04
1	0.03011	0.01984	0.02661	0.01872

THE ORIGINAL OBJECTIVE FUNCTION = 3135.8266602

THE RATIO OF OPTIMAL OBJECTIVE FUNCTION = 0.2382071

THE TOTAL OPTIMAL WEIGHT = 6.73263566E-01

OPTIMAL STRUCTURES OF TPS FOR PATCH = 1800
(WITH AVERAGE THICKNESS)

```
=============================================================   -----
                                                                  i
                 CRI-I  2.0          slab                       0.07815 FT   1962.3 F
                                                                  i
=============================================================   -----
                 RTV-560             thin skin                  0.00066 FT    546.0 F
=============================================================   -----
```

THICKNESS AND TEMPERATURE OF LAYERS FOR PATCH = 1800

PANEL	LAYER01		LAYER02	
1800001	0.03011	1962.31	0.00002	550.33
1800002	0.02975	1944.26	0.00002	550.33
1800003	0.02940	1926.21	0.00002	550.33
1800004	0.02904	1908.16	0.00002	550.33
1800005	0.02869	1890.11	0.00002	550.33
....				
....				
1800895	0.02008	1507.01	0.00002	550.33
1800896	0.01981	1493.37	0.00002	550.33
1800897	0.01954	1479.74	0.00002	550.33
1800898	0.01927	1466.10	0.00002	550.33
1800899	0.01900	1452.46	0.00002	550.33
1800900	0.01872	1438.83	0.00002	550.33

OPTIMIZATION SYSTEM FOR TPSSYM = 1900

TOTAL NUMBER OF DESIGN VARIABLES = 4
TOTAL NUMBER OF CONSTRAINS = 1840
TOTAL NUMBER OF TEMP. CONSTRAINS = 48
TOTAL NUMBER OF TEMP. PRINTOUTS = 6
WARNING: MODIFICATION EXEEDS ALLOWED VALUE

WARNING: MODIFICATION EXEEDS ALLOWED VALUE

WARNING: MODIFICATION EXEEDS ALLOWED VALUE

WARNING: MODIFICATION EXEEDS ALLOWED VALUE

```
MAXIMUM TEMPERATURE OF EACH LAYER VS OUTPUT TIMES
    X   0.1962E+04
  1.0 A                      A                      A                      A                      A
      I
      I
      I
      I
      I
      I
      I
      B                      B
      I                                             B                      B                      B
  0.0 +-----------+----------+-----------+----------+-----------+----------+-----------+----------+-----------+-----------+
      I
      I
      I
      I
      I
      I
      I
      I
 -1.0 +
      .00         .10         .20         .30         .40         .50         .60         .70         .80         .90
 1.00
                                                  TIME  ( X 2.350E+02 )
```

MAXIMUM TEMPERATURE OF EVERY LAYER

```
LAYER:        1        2
Tmax:   2400.33   550.33
Optv:   1962.29   480.34
```

VALUES OF DESIGN VARIABLES :

LAYER	DEV01	DEV02	DEV03	DEV04
1	0.02748	0.01987	0.02544	0.01973

THE ORIGINAL OBJECTIVE FUNCTION = 3135.8266602

THE RATIO OF OPTIMAL OBJECTIVE FUNCTION = 0.2313011

THE TOTAL OPTIMAL WEIGHT = 6.52450415E-01

OPTIMAL STRUCTURES OF TPS FOR PATCH = 1900
(WITH AVERAGE THICKNESS)

```
============================================================  -----
                                                                i
                    CRI-I  2.0           slab                 0.07589 FT    1962.3 F
                                                                i
============================================================  -----
                    RTV-560              thin skin            0.00066 FT     480.3 F
============================================================  -----
```

THICKNESS AND TEMPERATURE OF LAYERS FOR PATCH = 1900

PANEL	LAYER01		LAYER02	
1900001	0.02748	1962.29	0.00002	550.33
1900002	0.02721	1944.24	0.00002	550.33
1900003	0.02695	1926.19	0.00002	550.33
1900004	0.02669	1908.13	0.00002	550.33
1900005	0.02643	1890.08	0.00002	550.33
....				
....				
1900895	0.02072	1507.07	0.00002	550.33
1900896	0.02052	1493.43	0.00002	550.33
1900897	0.02032	1479.80	0.00002	550.33
1900898	0.02013	1466.17	0.00002	550.33
1900899	0.01993	1452.53	0.00002	550.33
1900900	0.01973	1438.90	0.00002	550.33

OPTIMIZATION SYSTEM FOR TPSSYM = 2000

```
TOTAL NUMBER OF DESIGN VARIABLES =     4
TOTAL NUMBER OF CONSTRAINS        = 1840
TOTAL NUMBER OF TEMP. CONSTRAINS =    48
TOTAL NUMBER OF TEMP. PRINTOUTS  =     6
WARNING: MODIFICATION EXEEDS ALLOWED VALUE
```

```
MAXIMUM TEMPERATURE OF EACH LAYER VS OUTPUT TIMES
    X   0.1922E+04
  1.0 A                      A                      A                      A                      A
      I
      I
      I
      I
      I
      I
      B
      I                      B
      I                                             B                      B                      B
  0.0 +-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+
      I
      I
      I
      I
      I
      I
      I
      I
 -1.0 +
      .00         .10         .20         .30         .40         .50         .60         .70         .80         .90
  1.00
                                              TIME  ( X 2.350E+02 )
```

MAXIMUM TEMPERATURE OF EVERY LAYER

```
LAYER:        1        2
Tmax:   2400.33   550.33
Optv:   1922.06   533.81
```

VALUES OF DESIGN VARIABLES :

LAYER	DEV01	DEV02	DEV03	DEV04
1	0.02440	0.02047	0.02315	0.01919

THE ORIGINAL OBJECTIVE FUNCTION = 3135.8266602

THE RATIO OF OPTIMAL OBJECTIVE FUNCTION = 0.2180511

THE TOTAL OPTIMAL WEIGHT = 6.19316060E-01

```
              OPTIMAL STRUCTURES OF TPS FOR PATCH =    2000
                     (WITH AVERAGE THICKNESS)
============================================================   -----
                                                                 i
                    CRI-I  2.0          slab                   0.07154 FT   1922.1 F
                                                                 i
============================================================   -----
                    RTV-560             thin skin              0.00066 FT    533.8 F
============================================================   -----
```

THICKNESS AND TEMPERATURE OF LAYERS FOR PATCH = 2000

PANEL	LAYER01		LAYER02	
2000001	0.02440	1922.06	0.00002	550.33
2000002	0.02427	1905.45	0.00002	550.33
2000003	0.02413	1888.84	0.00002	550.33
2000004	0.02400	1872.23	0.00002	550.33
2000005	0.02386	1855.62	0.00002	550.33

....

....

2000895	0.01988	1501.67	0.00002	550.33
2000896	0.01974	1489.40	0.00002	550.33
2000897	0.01960	1477.14	0.00002	550.33
2000898	0.01947	1464.87	0.00002	550.33
2000899	0.01933	1452.61	0.00002	550.33
2000900	0.01919	1440.34	0.00002	550.33

OPTIMIZATION SYSTEM FOR TPSSYM = 2100

TOTAL NUMBER OF DESIGN VARIABLES = 4
TOTAL NUMBER OF CONSTRAINS = 1840
TOTAL NUMBER OF TEMP. CONSTRAINS = 48
TOTAL NUMBER OF TEMP. PRINTOUTS = 6
WARNING: MODIFICATION EXEEDS ALLOWED VALUE

WARNING: MODIFICATION EXEEDS ALLOWED VALUE

WARNING: MODIFICATION EXEEDS ALLOWED VALUE

```
MAXIMUM TEMPERATURE OF EACH LAYER VS OUTPUT TIMES
    X   0.1922E+04
 1.0 A                      A                      A                      A                      A
     I
     I
     I
     I
     I
     I
     B
     I                      B
     I                                             B                      B                      B
 0.0 +-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+
     I
     I
     I
     I
     I
     I
     I
     I
     I
-1.0 +
    .00          .10          .20          .30          .40          .50          .60          .70          .80          .90
 1.00
                                                   TIME   ( X 2.350E+02 )
```

MAXIMUM TEMPERATURE OF EVERY LAYER

LAYER:	1	2
Tmax:	2400.33	550.33
Optv:	1922.01	509.15

VALUES OF DESIGN VARIABLES :

LAYER	DEV01	DEV02	DEV03	DEV04
1	0.02870	0.02059	0.02349	0.02126

THE ORIGINAL OBJECTIVE FUNCTION = 3135.8266602

THE RATIO OF OPTIMAL OBJECTIVE FUNCTION = 0.2351092

THE TOTAL OPTIMAL WEIGHT = 6.61571832E-01

OPTIMAL STRUCTURES OF TPS FOR PATCH = 2100
(WITH AVERAGE THICKNESS)

```
==========================================================   -----
                                                                 i
                    CRI-I  2.0          slab                 0.07714 FT    1922.0 F
                                                                 i
==========================================================   -----
                    RTV-560             thin skin            0.00066 FT     509.1 F
==========================================================   -----

         THICKNESS AND TEMPERATURE OF LAYERS FOR PATCH =     2100

   PANEL    LAYER01             LAYER02
 2100001    0.02870   1922.01   0.00002    550.33
 2100002    0.02842   1905.40   0.00002    550.33
 2100003    0.02814   1888.78   0.00002    550.33
 2100004    0.02786   1872.17   0.00002    550.33
 2100005    0.02758   1855.56   0.00002    550.33
...................................................................

...................................................................

2100895    0.02164   1501.66   0.00002    550.33
 2100896    0.02157   1489.40   0.00002    550.33
 2100897    0.02149   1477.13   0.00002    550.33
 2100898    0.02141   1464.86   0.00002    550.33
 2100899    0.02134   1452.59   0.00002    550.33
 2100900    0.02126   1440.32   0.00002    550.33

 T O T A L   M A S S   O F   B O T H   S I D E S :  0.43240E+02 (KG ),  C. G.  F R O M   X=0.   I S :  0.38270E+01 (M   )

                                        ****************************************
                                        ***                                  ***
                                        *** T P S O P T   T E R M I N A T E D ***
                                        ***                                  ***
                                        ***          N O R M A L L Y         ***
                                        ***                                  ***
                                        ***      12:40:39     10/19/2009     ***
                                        ***                                  ***
                                        ****************************************
```

Listing 9.6.3 Output of Mass change due to TPS: mass_tps.dat

```
   43.24017                                                                                  165.4823
```

9.7 Run SMB for Structural Design

Input Files:

File Name	Type	Remarks	See Listing
smb_run.inp	Standard input file	Required	Shown in listing 9.7.1
trajct.dat	Trajectory data generated by UPTOP	Inserted into the Standard input file smb_run.inp by the **INCLUDE** bulk data card	Shown in Listing 9.4.3
geom_data.dat	Aerodynamic mesh generated by UCDA	Imported by the ASSIGN AEROBASE executive control command	Not Shown

Output Files:

File Name	Type	Remarks	See Listing
smb_run.out	Standard output file	Print out results	Shown in Listing 9.7.2
RDOF_EIGEN.FREE	Eigenvalues and Eigenvectors of the beam model	Input file for TRIM and ASE analysis	Shown in Listing 9.7.3
masschng.dat	Mass of the structural skin designed by SMB	Input file for UCDA to update the change of weight due to structure	Shown in Listing 9.7.4

9.7.1 Descriptions of the Input File: SMB_RUN.INP (Shown in Listing 9.7.1)

The aerodynamic mesh of the SED configuration generated by UCDA is stored in the file "geom_data.dat" and imported into the SMB module by the executive control command shown as follows:

ASSIGN AEROBASE=geom_data.dat

Based on this aerodynamic mesh, SMB computes the width and height at 20 axial stations to approximate the cross section of the SED configuration as rectangular boxes. Then, the SMB module constructs a beam finite element model with 20 grid points and 19 beam elements along the x axis of the vehicle. The area moment of inertias of each beam element is calculated based on the size of the rectangular box at each axial station with the optimum skin thickness that is to be designed by the fully stressed design method. Meanwhile, the vehicle weight calculated by UCDA and stored in the file "geom_data.dat" is distributed at each grid points of the beam model to represent the non-structural weight of the SED configuration.

There is only one subcase defined by the case control command shown as follows:

BEAM=100

This case control command refers to a **BEAMFSD** bulk data card with ID = 100 in the bulk data section. In this **BEAMFSD** bulk data card, the material properties of the Aluminum along with a failure stress = $1.5\text{x}10^6$ is specified. It also defines an initial and minimum skin thickness as 0.00001and 0.000001, respectively, as well as a load factor of 1.5. The minimum skin thickness serves as a lower bound of thickness used by the Fully Stressed Design method. The load factor is used as a multiplication factor to the computed aerodynamic loads along on the trajectory. It should be noted that since the units of length and mass defined by UCDA for the SED configuration are in Meter and KG, respectively, the units of length and mass involved in the BEAMFSD input entries must be consistent with that of UCDA.

The trajectory is computed by UPTOP which is stored on the file "trajct.dat" that consists of one **TRAJCT** bulk data card with ID = 100 and one TIMESP bulk data card. The TRAJCT bulk data card is referred to by the **TRJLST** bulk data card with ID = 1. The TIMESP bulk data card is used only by the TPSOPT module and is not used by the SMB module. This trajectory file "trajct.dat" is automatically inserted into the bulk data section by the INCLUDE bulk data card shown as follows:

INCLUDE trajct.dat

9.7.2 Descriptions of the Standard Output File: smb_run.lut (Shown in Listing 9.7.2)

The standard output file first prints out the input bulk data cards in an alphabetic order. Then it shows the 20 grid point locations and the non-structural masses at each grid points. The total non-structural mass is 1277.0 KG that serves as the initial mass distribution of the beam model. The stiffness of the 19 beam elements with the initial skin thickness (0.00001) in term of EI and GJ is printed next.

After the Fully Stressed design computation is completed, SMB prints out the optimum thickness and the mass distribution of the beam model. This optimum thickness along with the initial thickness of the 19 beam element is shown in Figure 9.7.1. The total mass of the optimized structural model is 1285.8 KG which shows a 8.8 KG increase of mass due to the structural skin.

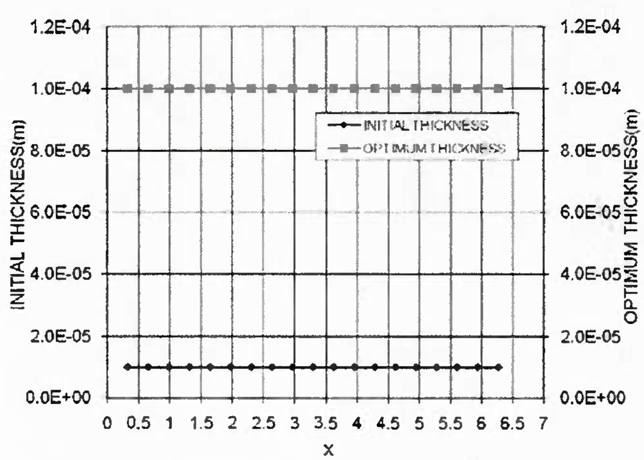


Figure 9.7.1 Optimum Thickness of the SED configuration

Next, the EI and GJ distribution followed by the natural frequencies of the optimized beam model are printed out. These EI and GJ distributions are depicted in Figure 9.7.2 and the natural frequencies of the first 5 elastic modes are shown in Table 9.7.2.

Finally, an NASTRAN input file of the optimized beam model is printed in the standard file that allows the user to use NASTRAN to verify the SMB solution.

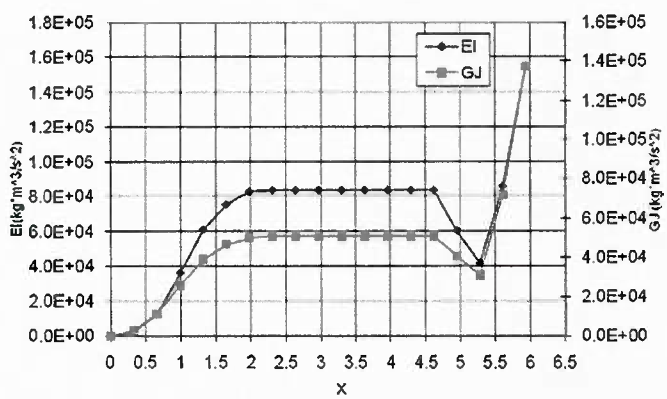


Figure 9.7.2 EI and GJ of the Optimized Beam Model for the SED Configuration

Table 9.7.2 Natural Frequencies of the First Elastic Modes

BENDING MODE NO.	NATURAL FREQUENCY(Hz)
1	1.91E+00
2	5.12E+00
3	9.64E+00
4	1.53E+01
5	2.91E+01

9.7.3 Other Output Files: RDOF_EIGEN.FREE (Shown in Listing 9.7.3) and masschng.dat (Shown in Listing 9.7.4)

The file "RDOF_EIGEN.FREE" contains the natural frequencies and generalized masses of the first 20 modes. Note that the first 3 modes are corresponding to the fore-aft, plunge, and pitch

rigid body modes. The first 3 elastic modes of the optimized beam model are depicted in Figure 9.7.3

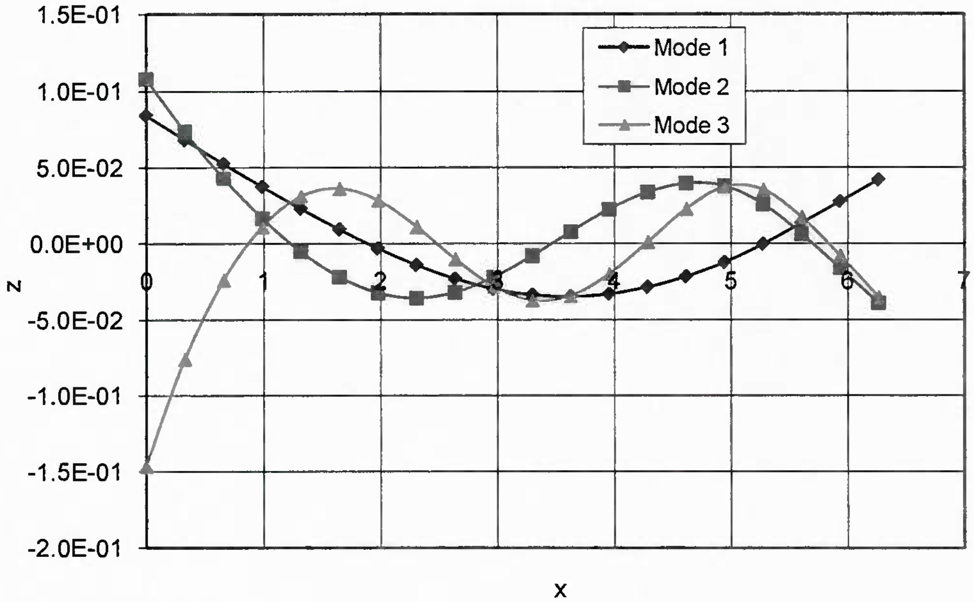


Figure 9.7.3 The First 3 Elastic Modes of the Optimized Beam Model

The file "masschng.dat" contains the locations of the 20 grid points and the incremental masses due to the structural skin at those 20 grid points. This file will be imported back to UCDA for the next design cycle to include the impact of the structural skin weight on the weight and center of gravity of the whole vehicle.

Listing 9.7.1 Standard Input File: smb_run.inp

```
assign aerobase=geom_data.dat,print=1
cend
title= SED Beam Model
echo=sort
subcase =1
   Beam=100
begin bulk
$
include 'trajct.dat'
$
beamfsd 100     1       6.895E092.592E09 .33     .00001 1.50     1.5E6
        .5      .05     .000005 6750.   .0001
trjlst  1
```

```
        100
Enddata
```

Listing 9.7.2 Standard Output File: smb_run.out

```
                         E X E C U T I V E   C O N T R O L   S U M M A R Y

                |...1...|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|..10...|

                assign aerobase=geom_data.dat,print=1
                cend

                           C A S E   C O N T R O L   S U M M A R Y

                        S I N G L E   P R E C I S I O N   C O M P U T A T I O N

                  M A X I M U M   A L L O C A B L E   M E M O R Y  = 800   M E G A B Y T E S

                |...1...|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|..10...|

                title= SED Beam Model
                echo=sort
                subcase =1
                Beam=100
                begin bulk

                           S O R T E D   B U L K   D A T A   E C H O
     CARD
     COUNT      |...1...|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|..10...|

        1 -     BEAMFSD 100     1       6.895E092.592E09.33     .00001  1.50    1.5E6
```

```
          .5      .05     .000005 6750.   .0001
TIMESP    201     0.000   60.000  120.000 180.000 240.000 282.000
TRAJCT    100     10
          12.0    6.9300  26068.  -0.130
          24.0    6.9400  25964.  -0.150
          36.0    6.9600  25815.  -0.160
          48.0    6.9700  25651.  -0.180
          60.0    6.9900  25507.  -0.200
          72.0    7.0100  25414.  -0.210
          84.0    7.0200  25395.  -0.230
          96.0    7.0300  25456.  -0.250
          108.0   7.0400  25590.  -0.260
          120.0   7.0500  25778.  -0.280
          132.0   7.0600  25990.  -0.300
          144.0   7.0700  26191.  -0.310
          156.0   7.0700  26347.  -0.330
          168.0   7.0800  26430.  -0.350
          180.0   7.0900  26425.  -0.360
          192.0   7.1000  26335.  -0.380
          204.0   7.1200  26181.  -0.400
          216.0   7.1500  26001.  -0.410
          228.0   7.1900  25850.  -0.430
          240.0   7.2300  25789.  -0.450
          252.0   7.2900  25878.  -0.460
          264.0   7.3500  26167.  -0.480
          276.0   7.4300  26694.  -0.500
          282.0   7.4700  27056.  -0.510          TECPLOT         1283.PLT
TRJLST    1
          100
ENDDATA
```

```
***************************************
*                                     *
*       SUBCASE      =       1        *
*       DISCIPLINE   = BEAM           *
*       BULK ENTRY ID =     100       *
*                                     *
***************************************
```

F I N I T E   E L E M E M T   M O D E L   D E S C R I P T I O N

GRID ID	COORDINATE X	Y	Z	CONCENTATED MASS
1	0.000	0.000	0.000	4.216
2	0.330	0.000	0.000	17.987
3	0.660	0.000	0.000	34.816
4	0.990	0.000	0.000	51.390
5	1.319	0.000	0.000	60.339
6	1.649	0.000	0.000	65.753
7	1.979	0.000	0.000	67.084
8	2.309	0.000	0.000	67.186
9	2.639	0.000	0.000	67.186
10	2.969	0.000	0.000	67.186
11	3.299	0.000	0.000	67.186
12	3.628	0.000	0.000	67.186
13	3.958	0.000	0.000	67.186
14	4.288	0.000	0.000	67.186
15	4.618	0.000	0.000	64.915
16	4.948	0.000	0.000	51.284
17	5.278	0.000	0.000	59.791
18	5.607	0.000	0.000	124.796
19	5.937	0.000	0.000	137.024
20	6.267	0.000	0.000	67.285

*TOTAL MASS =   0.12769855E+04

ELEMENT	CROSS SECTION(BOX)			MOMENT OF INERTIA			STIFFNESS	
ID	WIDTH	HEIGHT	THICKNESS	Izz	Iyy	J	BENDING(EI)	TORSION(GJ)
1	0.48E+0	0.11E+0	0.10E-4	0.32E-6	0.34E-7	0.10E-6	0.23733E+03	0.26721E+03
2	0.53E+0	0.24E+0	0.10E-4	0.59E-6	0.18E-6	0.43E-6	0.12571E+04	0.11191E+04
3	0.56E+0	0.39E+0	0.10E-4	0.90E-6	0.53E-6	0.10E-5	0.36286E+04	0.25992E+04
4	0.58E+0	0.49E+0	0.10E-4	0.11E-5	0.89E-6	0.15E-5	0.61152E+04	0.38984E+04
5	0.60E+0	0.53E+0	0.10E-4	0.13E-5	0.11E-5	0.18E-5	0.75459E+04	0.46416E+04
6	0.61E+0	0.55E+0	0.10E-4	0.14E-5	0.12E-5	0.19E-5	0.82579E+04	0.50121E+04
7	0.61E+0	0.55E+0	0.10E-4	0.14E-5	0.12E-5	0.20E-5	0.83490E+04	0.50585E+04
8	0.61E+0	0.55E+0	0.10E-4	0.14E-5	0.12E-5	0.20E-5	0.83490E+04	0.50585E+04
9	0.61E+0	0.55E+0	0.10E-4	0.14E-5	0.12E-5	0.20E-5	0.83490E+04	0.50585E+04
10	0.61E+0	0.55E+0	0.10E-4	0.14E-5	0.12E-5	0.20E-5	0.83490E+04	0.50585E+04
11	0.61E+0	0.55E+0	0.10E-4	0.14E-5	0.12E-5	0.20E-5	0.83490E+04	0.50585E+04
12	0.61E+0	0.55E+0	0.10E-4	0.14E-5	0.12E-5	0.20E-5	0.83490E+04	0.50585E+04
13	0.61E+0	0.55E+0	0.10E-4	0.14E-5	0.12E-5	0.20E-5	0.83490E+04	0.50585E+04
14	0.61E+0	0.55E+0	0.10E-4	0.14E-5	0.12E-5	0.20E-5	0.83490E+04	0.50585E+04
15	0.61E+0	0.48E+0	0.10E-4	0.13E-5	0.88E-6	0.16E-5	0.60474E+04	0.40427E+04
16	0.61E+0	0.40E+0	0.10E-4	0.11E-5	0.60E-6	0.12E-5	0.41643E+04	0.30892E+04
17	0.91E+0	0.48E+0	0.10E-4	0.32E-5	0.12E-5	0.28E-5	0.85587E+04	0.71520E+04
18	0.12E+1	0.57E+0	0.10E-4	0.71E-5	0.22E-5	0.53E-5	0.15436E+05	0.13680E+05
19	0.12E+1	0.56E+0	0.10E-4	0.71E-5	0.22E-5	0.52E-5	0.15222E+05	0.13530E+05

F U L L Y   S T R E S S E D   D E S I G N   R E S U L T

DESIGN VARIABLE : THICKNESS OF CROSS SECTION(BOX)

MINIMUM THICKNESS : 0.1000000E-03

ELEMENTS ID	INITIAL THICKNESS	OPTIMUM THICKNESS	INCREMENTS
1	0.99999997E-05	0.99999997E-04	0.90000001E-04
2	0.99999997E-05	0.99999997E-04	0.90000001E-04
3	0.99999997E-05	0.99999997E-04	0.90000001E-04
4	0.99999997E-05	0.99999997E-04	0.90000001E-04

5	0.99999997E-05	0.99999997E-04	0.90000001E-04
6	0.99999997E-05	0.99999997E-04	0.90000001E-04
7	0.99999997E-05	0.99999997E-04	0.90000001E-04
8	0.99999997E-05	0.99999997E-04	0.90000001E-04
9	0.99999997E-05	0.99999997E-04	0.90000001E-04
10	0.99999997E-05	0.99999997E-04	0.90000001E-04
11	0.99999997E-05	0.99999997E-04	0.90000001E-04
12	0.99999997E-05	0.99999997E-04	0.90000001E-04
13	0.99999997E-05	0.99999997E-04	0.90000001E-04
14	0.99999997E-05	0.99999997E-04	0.90000001E-04
15	0.99999997E-05	0.99999997E-04	0.90000001E-04
16	0.99999997E-05	0.99999997E-04	0.90000001E-04
17	0.99999997E-05	0.99999997E-04	0.90000001E-04
18	0.99999997E-05	0.99999997E-04	0.90000001E-04
19	0.99999997E-05	0.99999997E-04	0.90000001E-04

GRID ID	COORDINATE			CONCENTATED
	X	Y	Z	MASS
1	0.000	0.000	0.000	4.336
2	0.330	0.000	0.000	18.262
3	0.660	0.000	0.000	35.161
4	0.990	0.000	0.000	51.794
5	1.319	0.000	0.000	60.780
6	1.649	0.000	0.000	66.211
7	1.979	0.000	0.000	67.549
8	2.309	0.000	0.000	67.652
9	2.639	0.000	0.000	67.652
10	2.969	0.000	0.000	67.652
11	3.299	0.000	0.000	67.652
12	3.628	0.000	0.000	67.652
13	3.958	0.000	0.000	67.652
14	4.288	0.000	0.000	67.652
15	4.618	0.000	0.000	65.365
16	4.948	0.000	0.000	51.705
17	5.278	0.000	0.000	60.272
18	5.607	0.000	0.000	125.431

19	5.937	0.000	0.000	137.735
20	6.267	0.000	0.000	67.641

*TOTAL MASS = 0.12858082E+04

ELEMENT	CROSS SECTION(BOX)			MOMENT OF INERTIA			STIFFNESS	
ID	WIDTH	HEIGHT	THICKNESS	Izz	Iyy	J	BENDING(EI)	TORSION(GJ)
1	0.48E+0	0.11E+0	0.10E-3	0.32E-5	0:34E-6	0.10E-5	0.23776E+04	0.26765E+04
2	0.53E+0	0.24E+0	0.10E-3	0.59E-5	0.18E-5	0.43E-5	0.12583E+05	0.11201E+05
3	0.56E+0	0.39E+0	0.10E-3	0.90E-5	0.53E-5	0.10E-4	0.36309E+05	0.26007E+05
4	0.58E+0	0.49E+0	0.10E-3	0.11E-4	0.89E-5	0.15E-4	0.61184E+05	0.39004E+05
5	0.60E+0	0.53E+0	0.10E-3	0.13E-4	0.11E-4	0.18E-4	0.75496E+05	0.46439E+05
6	0.61E+0	0.55E+0	0.10E-3	0.14E-4	0.12E-4	0.19E-4	0.82619E+05	0.50145E+05
7	0.61E+0	0.55E+0	0.10E-3	0.14E-4	0.12E-4	0.20E-4	0.83529E+05	0.50609E+05
8	0.61E+0	0.55E+0	0.10E-3	0.14E-4	0.12E-4	0.20E-4	0.83529E+05	0.50609E+05
9	0.61E+0	0.55E+0	0.10E-3	0.14E-4	0.12E-4	0.20E-4	0.83529E+05	0.50609E+05
10	0.61E+0	0.55E+0	0.10E-3	0.14E-4	0.12E-4	0.20E-4	0.83529E+05	0.50609E+05
11	0.61E+0	0.55E+0	0.10E-3	0.14E-4	0.12E-4	0.20E-4	0.83529E+05	0.50609E+05
12	0.61E+0	0.55E+0	0.10E-3	0.14E-4	0.12E-4	0.20E-4	0.83529E+05	0.50609E+05
13	0.61E+0	0.55E+0	0.10E-3	0.14E-4	0.12E-4	0.20E-4	0.83529E+05	0.50609E+05
14	0.61E+0	0.55E+0	0.10E-3	0.14E-4	0.12E-4	0.20E-4	0.83529E+05	0.50609E+05
15	0.61E+0	0.48E+0	0.10E-3	0.13E-4	0.88E-5	0.16E-4	0.60506E+05	0.40447E+05
16	0.61E+0	0.40E+0	0.10E-3	0.11E-4	0.60E-5	0.12E-4	0.41668E+05	0.30910E+05
17	0.91E+0	0.48E+0	0.10E-3	0.32E-4	0.12E-4	0.28E-4	0.85629E+05	0.71551E+05
18	0.12E+1	0.57E+0	0.10E-3	0.71E-4	0.22E-4	0.53E-4	0.15443E+06	0.13685E+06
19	0.12E+1	0.56E+0	0.10E-3	0.71E-4	0.22E-4	0.52E-4	0.15228E+06	0.13535E+06

M A X I M U M   S T R E S S   A F T E R   F U L L Y   S T R E S S E D   D E S I G N

LOAD CASE NUMBER	ELEMENT ID	STRESS
1	10	0.81600E+05
2	10	0.78126E+05
3	10	0.70777E+05
4	10	0.78910E+05

5 10 0.68358E+05

REAL EIGENVALUES OF OPTIMUM SYSTEM

MODE NO.	EXTRACTION ORDER	EIGENVALUE	RADIANS	CYCLES	GENERALIZED MASS	GENERALIZED STIFFNESS
1	1	0.581375E-03	0.241117E-01	0.383750E-02	0.100000E+01	0.581375E-03
2	2	0.551645E-02	0.742728E-01	0.118209E-01	0.100000E+01	0.551645E-02
3	3	0.133828E-01	0.115684E+00	0.184117E-01	0.100000E+01	0.133828E-01
4	4	0.144711E+03	0.120296E+02	0.191457E+01	0.100000E+01	0.144711E+03
5	5	0.103320E+04	0.321435E+02	0.511579E+01	0.100000E+01	0.103320E+04
6	6	0.197907E+04	0.444868E+02	0.708029E+01	0.100000E+01	0.197907E+04
7	7	0.366857E+04	0.605687E+02	0.963981E+01	0.100000E+01	0.366857E+04
8	8	0.829653E+04	0.910853E+02	0.144967E+02	0.100000E+01	0.829653E+04
9	9	0.922441E+04	0.960438E+02	0.152858E+02	0.100000E+01	0.922441E+04
10	10	0.188928E+05	0.137451E+03	0.218760E+02	0.100000E+01	0.188928E+05
11	11	0.196447E+05	0.140160E+03	0.223071E+02	0.100000E+01	0.196447E+05
12	12	0.344090E+05	0.185497E+03	0.295227E+02	0.100000E+01	0.344090E+05
13	13	0.355948E+05	0.188666E+03	0.300271E+02	0.100000E+01	0.355948E+05
14	14	0.541596E+05	0.232722E+03	0.370389E+02	0.100000E+01	0.541596E+05
15	15	0.581265E+05	0.241094E+03	0.383714E+02	0.100000E+01	0.581265E+05
16	16	0.718023E+05	0.267959E+03	0.426471E+02	0.100000E+01	0.718023E+05
17	17	0.916527E+05	0.302742E+03	0.481829E+02	0.100000E+01	0.916527E+05
18	18	0.925040E+05	0.304145E+03	0.484061E+02	0.100000E+01	0.925040E+05
19	19	0.116102E+06	0.340738E+03	0.542301E+02	0.100000E+01	0.116102E+06
20	20	0.140350E+06	0.374633E+03	0.596246E+02	0.100000E+01	0.140350E+06
21	21	0.141858E+06	0.376641E+03	0.599442E+02	0.100000E+01	0.141858E+06
22	22	0.166759E+06	0.408361E+03	0.649927E+02	0.100000E+01	0.166759E+06
23	23	0.189410E+06	0.435212E+03	0.692662E+02	0.100000E+01	0.189410E+06
24	24	0.205525E+06	0.453349E+03	0.721527E+02	0.100000E+01	0.205525E+06
25	25	0.206228E+06	0.454124E+03	0.722760E+02	0.100000E+01	0.206228E+06
26	26	0.224616E+06	0.473937E+03	0.754294E+02	0.100000E+01	0.224616E+06
27	27	0.246542E+06	0.496530E+03	0.790251E+02	0.100000E+01	0.246542E+06
28	28	0.266190E+06	0.515936E+03	0.821138E+02	0.100000E+01	0.266190E+06
29	29	0.280797E+06	0.529903E+03	0.843367E+02	0.100000E+01	0.280797E+06
30	30	0.293112E+06	0.541398E+03	0.861662E+02	0.100000E+01	0.293112E+06
31	31	0.293772E+06	0.542007E+03	0.862631E+02	0.100000E+01	0.293772E+06

32	32	0.327103E+06	0.571929E+03	0.910253E+02	0.100000E+01	0.327103E+06
33	33	0.407257E+06	0.638167E+03	0.101567E+03	0.100000E+01	0.407257E+06
34	34	0.539381E+06	0.734426E+03	0.116887E+03	0.100000E+01	0.539381E+06
35	35	0.704143E+06	0.839132E+03	0.133552E+03	0.100000E+01	0.704143E+06
36	36	0.764870E+06	0.874569E+03	0.139192E+03	0.100000E+01	0.764870E+06
37	37	0.908416E+06	0.953109E+03	0.151692E+03	0.100000E+01	0.908416E+06
38	38	0.111247E+07	0.105474E+04	0.167867E+03	0.100000E+01	0.111247E+07
39	39	0.133479E+07	0.115533E+04	0.183876E+03	0.100000E+01	0.133479E+07
40	40	0.155555E+07	0.124722E+04	0.198501E+03	0.100000E+01	0.155555E+07
41	41	0.581352E+10	0.762464E+05	0.121350E+05	0.100000E+01	0.581352E+10
42	42	0.920630E+10	0.959495E+05	0.152708E+05	0.100000E+01	0.920630E+10
43	43	0.129254E+11	0.113690E+06	0.180943E+05	0.100000E+01	0.129254E+11
44	44	0.135299E+11	0.116318E+06	0.185126E+05	0.100000E+01	0.135299E+11
45	45	0.149468E+11	0.122257E+06	0.194578E+05	0.100000E+01	0.149468E+11
46	46	0.159612E+11	0.126338E+06	0.201073E+05	0.100000E+01	0.159612E+11
47	47	0.175159E+11	0.132348E+06	0.210638E+05	0.100000E+01	0.175159E+11
48	48	0.193723E+11	0.139184E+06	0.221519E+05	0.100000E+01	0.193723E+11
49	49	0.209807E+11	0.144847E+06	0.230531E+05	0.100000E+01	0.209807E+11
50	50	0.227686E+11	0.150893E+06	0.240153E+05	0.100000E+01	0.227686E+11
51	51	0.250535E+11	0.158283E+06	0.251915E+05	0.100000E+01	0.250535E+11
52	52	0.275608E+11	0.166014E+06	0.264220E+05	0.100000E+01	0.275608E+11
53	53	0.301299E+11	0.173580E+06	0.276260E+05	0.100000E+01	0.301299E+11
54	54	0.319905E+11	0.178859E+06	0.284663E+05	0.100000E+01	0.319905E+11
55	55	0.343759E+11	0.185407E+06	0.295085E+05	0.100000E+01	0.343759E+11
56	56	0.373675E+11	0.193307E+06	0.307657E+05	0.100000E+01	0.373675E+11
57	57	0.389052E+11	0.197244E+06	0.313924E+05	0.100000E+01	0.389052E+11
58	58	0.402897E+11	0.200723E+06	0.319460E+05	0.100000E+01	0.402897E+11
59	59	0.427208E+11	0.206690E+06	0.328958E+05	0.100000E+01	0.427208E+11
60	60	0.443468E+11	0.210587E+06	0.335159E+05	0.100000E+01	0.443468E+11

N A S T R A N   I N P U T   D E C K

SOL 101

```
CEND
SUBCASE =        1
LOAD =       1
DISP = ALL
STRESS = ALL
SUBCASE =        2
LOAD =       2
DISP = ALL
STRESS = ALL
SUBCASE =        3
LOAD =       3
DISP = ALL
STRESS = ALL
SUBCASE =        4
LOAD =       4
DISP = ALL
STRESS = ALL
SUBCASE =        5
LOAD =       5
DISP = ALL
STRESS = ALL
BEGIN BULK
PARAM, INREL, -1
PARAM, GRDPNT,1
SUPORT,1,123456
GRID           1           0.000   0.000   0.000
GRID           2           0.330   0.000   0.000
GRID           3           0.660   0.000   0.000
GRID           4           0.990   0.000   0.000
GRID           5           1.319   0.000   0.000
GRID           6           1.649   0.000   0.000
GRID           7           1.979   0.000   0.000
GRID           8           2.309   0.000   0.000
GRID           9           2.639   0.000   0.000
GRID          10           2.969   0.000   0.000
GRID          11           3.299   0.000   0.000
```

GRID	12		3.628	0.000	0.000		
GRID	13		3.958	0.000	0.000		
GRID	14		4.288	0.000	0.000		
GRID	15		4.618	0.000	0.000		
GRID	16		4.948	0.000	0.000		
GRID	17		5.278	0.000	0.000		
GRID	18		5.607	0.000	0.000		
GRID	19		5.937	0.000	0.000		
GRID	20		6.267	0.000	0.000		
CBAR	1	1	1	2	1.000	1.000	0.000
CBAR	2	2	2	3	1.000	1.000	0.000
CBAR	3	3	3	4	1.000	1.000	0.000
CBAR	4	4	4	5	1.000	1.000	0.000
CBAR	5	5	5	6	1.000	1.000	0.000
CBAR	6	6	6	7	1.000	1.000	0.000
CBAR	7	7	7	8	1.000	1.000	0.000
CBAR	8	8	8	9	1.000	1.000	0.000
CBAR	9	9	9	10	1.000	1.000	0.000
CBAR	10	10	10	11	1.000	1.000	0.000
CBAR	11	11	11	12	1.000	1.000	0.000
CBAR	12	12	12	13	1.000	1.000	0.000
CBAR	13	13	13	14	1.000	1.000	0.000
CBAR	14	14	14	15	1.000	1.000	0.000
CBAR	15	15	15	16	1.000	1.000	0.000
CBAR	16	16	16	17	1.000	1.000	0.000
CBAR	17	17	17	18	1.000	1.000	0.000
CBAR	18	18	18	19	1.000	1.000	0.000
CBAR	19	19	19	20	1.000	1.000	0.000
FORCE	1	1	0	-0.65E-1	0.000	0.000	1.000
FORCE	1	2	0	-0.11E+0	0.000	0.000	1.000
FORCE	1	3	0	-0.29E+0	0.000	0.000	1.000
FORCE	1	4	0	-0.11E+1	0.000	0.000	1.000
FORCE	1	5	0	-0.22E+1	0.000	0.000	1.000
FORCE	1	6	0	-0.94E-1	0.000	0.000	1.000
FORCE	1	7	0	0.30E+0	0.000	0.000	1.000
FORCE	1	8	0	0.65E+0	0.000	0.000	1.000

FORCE	1	9	0 0.88E+0	0.000	0.000	1.000
FORCE	1	10	0 0.65E+0	0.000	0.000	1.000
FORCE	1	11	0 0.65E+0	0.000	0.000	1.000
FORCE	1	12	0 0.65E+0	0.000	0.000	1.000
FORCE	1	13	0 0.65E+0	0.000	0.000	1.000
FORCE	1	14	0 0.65E+0	0.000	0.000	1.000
FORCE	1	15	0 0.65E+0	0.000	0.000	1.000
FORCE	1	16	0 0.65E+0	0.000	0.000	1.000
FORCE	1	17	0 0.65E+0	0.000	0.000	1.000
FORCE	1	18	0 0.65E+0	0.000	0.000	1.000
FORCE	1	19	0 0.65E+0	0.000	0.000	1.000
FORCE	1	20	0 0.44E+0	0.000	0.000	1.000
FORCE	2	1	0-0.62E-1	0.000	0.000	1.000
FORCE	2	2	0-0.10E+0	0.000	0.000	1.000
FORCE	2	3	0-0.28E+0	0.000	0.000	1.000
FORCE	2	4	0-0.10E+1	0.000	0.000	1.000
FORCE	2	5	0-0.21E+1	0.000	0.000	1.000
FORCE	2	6	0-0.95E-1	0.000	0.000	1.000
FORCE	2	7	0 0.29E+0	0.000	0.000	1.000
FORCE	2	8	0 0.61E+0	0.000	0.000	1.000
FORCE	2	9	0 0.83E+0	0.000	0.000	1.000
FORCE	2	10	0 0.61E+0	0.000	0.000	1.000
FORCE	2	11	0 0.62E+0	0.000	0.000	1.000
FORCE	2	12	0 0.61E+0	0.000	0.000	1.000
FORCE	2	13	0 0.61E+0	0.000	0.000	1.000
FORCE	2	14	0 0.62E+0	0.000	0.000	1.000
FORCE	2	15	0 0.61E+0	0.000	0.000	1.000
FORCE	2	16	0 0.61E+0	0.000	0.000	1.000
FORCE	2	17	0 0.61E+0	0.000	0.000	1.000
FORCE	2	18	0 0.62E+0	0.000	0.000	1.000
FORCE	2	19	0 0.61E+0	0.000	0.000	1.000
FORCE	2	20	0 0.42E+0	0.000	0.000	1.000
FORCE	3	1	0-0.55E-1	0.000	0.000	1.000
FORCE	3	2	0-0.92E-1	0.000	0.000	1.000
FORCE	3	3	0-0.25E+0	0.000	0.000	1.000
FORCE	3	4	0-0.96E+0	0.000	0.000	1.000

FORCE	3	5	0-0.19E+1	0.000	0.000	1.000
FORCE	3	6	0-0.89E-1	0.000	0.000	1.000
FORCE	3	7	0 0.26E+0	0.000	0.000	1.000
FORCE	3	8	0 0.55E+0	0.000	0.000	1.000
FORCE	3	9	0 0.75E+0	0.000	0.000	1.000
FORCE	3	10	0 0.55E+0	0.000	0.000	1.000
FORCE	3	11	0 0.55E+0	0.000	0.000	1.000
FORCE	3	12	0 0.55E+0	0.000	0.000	1.000
FORCE	3	13	0 0.55E+0	0.000	0.000	1.000
FORCE	3	14	0 0.55E+0	0.000	0.000	1.000
FORCE	3	15	0 0.55E+0	0.000	0.000	1.000
FORCE	3	16	0 0.55E+0	0.000	0.000	1.000
FORCE	3	17	0 0.55E+0	0.000	0.000	1.000
FORCE	3	18	0 0.55E+0	0.000	0.000	1.000
FORCE	3	19	0 0.55E+0	0.000	0.000	1.000
FORCE	3	20	0 0.37E+0	0.000	0.000	1.000
FORCE	4	1	0-0.60E-1	0.000	0.000	1.000
FORCE	4	2	0-0.10E+0	0.000	0.000	1.000
FORCE	4	3	0-0.28E+0	0.000	0.000	1.000
FORCE	4	4	0-0.11E+1	0.000	0.000	1.000
FORCE	4	5	0-0.22E+1	0.000	0.000	1.000
FORCE	4	6	0-0.11E+0	0.000	0.000	1.000
FORCE	4	7	0 0.28E+0	0.000	0.000	1.000
FORCE	4	8	0 0.60E+0	0.000	0.000	1.000
FORCE	4	9	0 0.82E+0	0.000	0.000	1.000
FORCE	4	10	0 0.60E+0	0.000	0.000	1.000
FORCE	4	11	0 0.61E+0	0.000	0.000	1.000
FORCE	4	12	0 0.60E+0	0.000	0.000	1.000
FORCE	4	13	0 0.60E+0	0.000	0.000	1.000
FORCE	4	14	0 0.61E+0	0.000	0.000	1.000
FORCE	4	15	0 0.60E+0	0.000	0.000	1.000
FORCE	4	16	0 0.60E+0	0.000	0.000	1.000
FORCE	4	17	0 0.60E+0	0.000	0.000	1.000
FORCE	4	18	0 0.61E+0	0.000	0.000	1.000
FORCE	4	19	0 0.61E+0	0.000	0.000	1.000
FORCE	4	20	0 0.41E+0	0.000	0.000	1.000

```
FORCE          5        1         0-0.51E-1   0.000    0.000    1.000

FORCE          5        2         0-0.87E-1   0.000    0.000    1.000

FORCE          5        3         0-0.25E+0   0.000    0.000    1.000

FORCE          5        4         0-0.95E+0   0.000    0.000    1.000

FORCE          5        5         0-0.19E+1   0.000    0.000    1.000

FORCE          5        6         0-0.10E+0   0.000    0.000    1.000

FORCE          5        7         0 0.24E+0   0.000    0.000    1.000

FORCE          5        8         0 0.51E+0   0.000    0.000    1.000

FORCE          5        9         0 0.70E+0   0.000    0.000    1.000

FORCE          5       10         0 0.51E+0   0.000    0.000    1.000

FORCE          5       11         0 0.52E+0   0.000    0.000    1.000

FORCE          5       12         0 0.51E+0   0.000    0.000    1.000

FORCE          5       13         0 0.51E+0   0.000    0.000    1.000

FORCE          5       14         0 0.52E+0   0.000    0.000    1.000

FORCE          5       15         0 0.51E+0   0.000    0.000    1.000

FORCE          5       16         0 0.51E+0   0.000    0.000    1.000

FORCE          5       17         0 0.51E+0   0.000    0.000    1.000

FORCE          5       18         0 0.52E+0   0.000    0.000    1.000

FORCE          5       19         0 0.52E+0   0.000    0.000    1.000

FORCE          5       20         0 0.35E+0   0.000    0.000    1.000

PBAR           1        1.120E-03.323E-05.345E-06.103E-05

        -.24E+000.57E-010.24E+000.57E-010.24E+00-.57E-01-.24E+00-.57E-01

PBAR           2        1.155E-03.587E-05.182E-05.432E-05

        -.26E+000.12E+000.26E+000.12E+000.26E+00-.12E+00-.26E+00-.12E+00

PBAR           3        1.190E-03.898E-05.527E-05.100E-04

        -.28E+000.20E+000.28E+000.20E+000.28E+00-.20E+00-.28E+00-.20E+00

PBAR           4        1.214E-03.115E-04.887E-05.150E-04

        -.29E+000.24E+000.29E+000.24E+000.29E+00-.24E+00-.29E+00-.24E+00

PBAR           5        1.226E-03.131E-04.109E-04.179E-04

        -.30E+000.27E+000.30E+000.27E+000.30E+00-.27E+00-.30E+00-.27E+00

PBAR           6        1.232E-03.139E-04.120E-04.193E-04

        -.30E+000.27E+000.30E+000.27E+000.30E+00-.27E+00-.30E+00-.27E+00

PBAR           7        1.232E-03.140E-04.121E-04.195E-04

        -.30E+000.28E+000.30E+000.28E+000.30E+00-.28E+00-.30E+00-.28E+00

PBAR           8        1.232E-03.140E-04.121E-04.195E-04

        -.30E+000.28E+000.30E+000.28E+000.30E+00-.28E+00-.30E+00-.28E+00
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PBAR          9       1.232E-03.140E-04.121E-04.195E-04
        -.30E+000.28E+000.30E+000.28E+000.30E+00-.28E+00-.30E+00-.28E+00
PBAR         10       1.232E-03.140E-04.121E-04.195E-04
        -.30E+000.28E+000.30E+000.28E+000.30E+00-.28E+00-.30E+00-.28E+00
PBAR         11       1.232E-03.140E-04.121E-04.195E-04
        -.30E+000.28E+000.30E+000.28E+000.30E+00-.28E+00-.30E+00-.28E+00
PBAR         12       1.232E-03.140E-04.121E-04.195E-04
        -.30E+000.28E+000.30E+000.28E+000.30E+00-.28E+00-.30E+00-.28E+00
PBAR         13       1.232E-03.140E-04.121E-04.195E-04
        -.30E+000.28E+000.30E+000.28E+000.30E+00-.28E+00-.30E+00-.28E+00
PBAR         14       1.232E-03.140E-04.121E-04.195E-04
        -.30E+000.28E+000.30E+000.28E+000.30E+00-.28E+00-.30E+00-.28E+00
PBAR         15       1.217E-03.127E-04.878E-05.156E-04
        -.30E+000.24E+000.30E+000.24E+000.30E+00-.24E+00-.30E+00-.24E+00
PBAR         16       1.203E-03.113E-04.604E-05.119E-04
        -.30E+000.20E+000.30E+000.20E+000.30E+00-.20E+00-.30E+00-.20E+00
PBAR         17       1.278E-03.325E-04.124E-04.276E-04
        -.45E+000.24E+000.45E+000.24E+000.45E+00-.24E+00-.45E+00-.24E+00
PBAR         18       1.355E-03.709E-04.224E-04.528E-04
        -.60E+000.28E+000.60E+000.28E+000.60E+00-.28E+00-.60E+00-.28E+00
PBAR         19       1.354E-03.706E-04.221E-04.522E-04
        -.60E+000.28E+000.60E+000.28E+000.60E+00-.28E+00-.60E+00-.28E+00
CONM2        21       1       0.43E+1
        1.E-6           1.E-6                   1.E-6
CONM2        22       2       0.18E+2
        1.E-6           1.E-6                   1.E-6
CONM2        23       3       0.35E+2
        1.E-6           1.E-6                   1.E-6
CONM2        24       4       0.52E+2
        1.E-6           1.E-6                   1.E-6
CONM2        25       5       0.61E+2
        1.E-6           1.E-6                   1.E-6
CONM2        26       6       0.66E+2
        1.E-6           1.E-6                   1.E-6
CONM2        27       7       0.68E+2
        1.E-6           1.E-6                   1.E-6
```

```
CONM2          28        8          0.68E+2
        1.E-6          1.E-6                    1.E-6
CONM2          29        9          0.68E+2
        1.E-6          1.E-6                    1.E-6
CONM2          30       10          0.68E+2
        1.E-6          1.E-6                    1.E-6
CONM2          31       11          0.68E+2
        1.E-6          1.E-6                    1.E-6
CONM2          32       12          0.68E+2
        1.E-6          1.E-6                    1.E-6
CONM2          33       13          0.68E+2
        1.E-6          1.E-6                    1.E-6
CONM2          34       14          0.68E+2
        1.E-6          1.E-6                    1.E-6
CONM2          35       15          0.65E+2
        1.E-6          1.E-6                    1.E-6
CONM2          36       16          0.52E+2
        1.E-6          1.E-6                    1.E-6
CONM2          37       17          0.60E+2
        1.E-6          1.E-6                    1.E-6
CONM2          38       18          0.13E+3
        1.E-6          1.E-6                    1.E-6
CONM2          39       19          0.14E+3
        1.E-6          1.E-6                    1.E-6
CONM2          40       20          0.68E+2
        1.E-6          1.E-6                    1.E-6
MAT1            1 0.7E+10 0.3E+10 0.33E+0
ENDDATA
```

```
                                        ****************************************
                                        ***                                  ***
                                        *** S   M   B    T E R M I N A T E D ***
                                        ***                                  ***
                                        ***           N O R M A L L Y        ***
```

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***                                   ***

***      10:58:06     10/13/2009      ***

***                                   ***

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Listing 9.7.3 Eigenvalues and Eigenvectors of the Beam Model: RDOF_EIGEN.FREE

```
       20          20
        1        0.00000000E+00    0.00000000E+00    0.00000000E+00
        2        0.32985264E+00    0.00000000E+00    0.00000000E+00
        3        0.65970528E+00    0.00000000E+00    0.00000000E+00
        4        0.98955792E+00    0.00000000E+00    0.00000000E+00
        5        0.13194106E+01    0.00000000E+00    0.00000000E+00
        6        0.16492631E+01    0.00000000E+00    0.00000000E+00
        7        0.19791158E+01    0.00000000E+00    0.00000000E+00
        8        0.23089683E+01    0.00000000E+00    0.00000000E+00
        9        0.26388211E+01    0.00000000E+00    0.00000000E+00
       10        0.29686737E+01    0.00000000E+00    0.00000000E+00
       11        0.32985263E+01    0.00000000E+00    0.00000000E+00
       12        0.36283789E+01    0.00000000E+00    0.00000000E+00
       13        0.39582317E+01    0.00000000E+00    0.00000000E+00
       14        0.42880840E+01    0.00000000E+00    0.00000000E+00
       15        0.46179366E+01    0.00000000E+00    0.00000000E+00
       16        0.49477897E+01    0.00000000E+00    0.00000000E+00
       17        0.52776423E+01    0.00000000E+00    0.00000000E+00
       18        0.56074948E+01    0.00000000E+00    0.00000000E+00
       19        0.59373474E+01    0.00000000E+00    0.00000000E+00
       20        0.62672000E+01    0.00000000E+00    0.00000000E+00
$MODE           1
  0.24111725E-01    0.10000000E+01
        1  -0.278876328E-01   0.000000000E+00   0.112659199E-05   0.000000000E+00  -0.131874517E-05   0.000000000E+00
        2  -0.278876328E-01   0.000000000E+00   0.156158370E-05   0.000000000E+00  -0.131874616E-05   0.000000000E+00
        3  -0.278876348E-01   0.000000000E+00   0.199657550E-05   0.000000000E+00  -0.131874523E-05   0.000000000E+00
        4  -0.278876364E-01   0.000000000E+00   0.243156709E-05   0.000000000E+00  -0.131874513E-05   0.000000000E+00
        5  -0.278876407E-01   0.000000000E+00   0.286655839E-05   0.000000000E+00  -0.131874271E-05   0.000000000E+00
        6  -0.278876445E-01   0.000000000E+00   0.330154774E-05   0.000000000E+00  -0.131873266E-05   0.000000000E+00
        7  -0.278876480E-01   0.000000000E+00   0.373653169E-05   0.000000000E+00  -0.131870764E-05   0.000000000E+00
        8  -0.278876513E-01   0.000000000E+00   0.417150394E-05   0.000000000E+00  -0.131866388E-05   0.000000000E+00
        9  -0.278876515E-01   0.000000000E+00   0.460645919E-05   0.000000000E+00  -0.131860165E-05   0.000000000E+00
       10  -0.278876486E-01   0.000000000E+00   0.504139134E-05   0.000000000E+00  -0.131852787E-05   0.000000000E+00
       11  -0.278876455E-01   0.000000000E+00   0.547629834E-05   0.000000000E+00  -0.131844911E-05   0.000000000E+00
       12  -0.278876421E-01   0.000000000E+00   0.591117857E-05   0.000000000E+00  -0.131836563E-05   0.000000000E+00
       13  -0.278876385E-01   0.000000000E+00   0.634603075E-05   0.000000000E+00  -0.131827717E-05   0.000000000E+00
       14  -0.278876376E-01   0.000000000E+00   0.678085319E-05   0.000000000E+00  -0.131819208E-05   0.000000000E+00
       15  -0.278876393E-01   0.000000000E+00   0.721564925E-05   0.000000000E+00  -0.131811303E-05   0.000000000E+00
       16  -0.278876440E-01   0.000000000E+00   0.765041483E-05   0.000000000E+00  -0.131800367E-05   0.000000000E+00
       17  -0.278876521E-01   0.000000000E+00   0.808513655E-05   0.000000000E+00  -0.131785376E-05   0.000000000E+00
       18  -0.278876578E-01   0.000000000E+00   0.851982451E-05   0.000000000E+00  -0.131780157E-05   0.000000000E+00
       19  -0.278876601E-01   0.000000000E+00   0.895450277E-05   0.000000000E+00  -0.131779307E-05   0.000000000E+00
       20  -0.278876603E-01   0.000000000E+00   0.938918049E-05   0.000000000E+00  -0.131779433E-05   0.000000000E+00
$MODE           2
  0.74272821E-01    0.10000000E+01
        1  -0.590135654E-05   0.000000000E+00  -0.310373703E-01   0.000000000E+00  -0.855877568E-03   0.000000000E+00
        2  -0.590135649E-05   0.000000000E+00  -0.307550586E-01   0.000000000E+00  -0.855861192E-03   0.000000000E+00
        3  -0.590135672E-05   0.000000000E+00  -0.304727516E-01   0.000000000E+00  -0.855854660E-03   0.000000000E+00
        4  -0.590135661E-05   0.000000000E+00  -0.301904499E-01   0.000000000E+00  -0.855826006E-03   0.000000000E+00
        5  -0.590135681E-05   0.000000000E+00  -0.299081556E-01   0.000000000E+00  -0.855817760E-03   0.000000000E+00
        6  -0.590135657E-05   0.000000000E+00  -0.296258560E-01   0.000000000E+00  -0.855869346E-03   0.000000000E+00
        7  -0.590135589E-05   0.000000000E+00  -0.293435221E-01   0.000000000E+00  -0.856034073E-03   0.000000000E+00
        8  -0.590135477E-05   0.000000000E+00  -0.290611107E-01   0.000000000E+00  -0.856338226E-03   0.000000000E+00
        9  -0.590135258E-05   0.000000000E+00  -0.287785773E-01   0.000000000E+00  -0.856769639E-03   0.000000000E+00
       10  -0.590134933E-05   0.000000000E+00  -0.284958867E-01   0.000000000E+00  -0.857277176E-03   0.000000000E+00
       11  -0.590134563E-05   0.000000000E+00  -0.282130243E-01   0.000000000E+00  -0.857809629E-03   0.000000000E+00
       12  -0.590134148E-05   0.000000000E+00  -0.279299840E-01   0.000000000E+00  -0.858353217E-03   0.000000000E+00
       13  -0.590133687E-05   0.000000000E+00  -0.276467643E-01   0.000000000E+00  -0.858893951E-03   0.000000000E+00
       14  -0.590133242E-05   0.000000000E+00  -0.273633731E-01   0.000000000E+00  -0.859381798E-03   0.000000000E+00
       15  -0.590132838E-05   0.000000000E+00  -0.270798332E-01   0.000000000E+00  -0.859803354E-03   0.000000000E+00
       16  -0.590132390E-05   0.000000000E+00  -0.267961365E-01   0.000000000E+00  -0.860325023E-03   0.000000000E+00
       17  -0.590132141E-05   0.000000000E+00  -0.265122538E-01   0.000000000E+00  -0.860901326E-03   0.000000000E+00
       18  -0.590131983E-05   0.000000000E+00  -0.262282551E-01   0.000000000E+00  -0.861049662E-03   0.000000000E+00
       19  -0.590131938E-05   0.000000000E+00  -0.259442311E-01   0.000000000E+00  -0.861068348E-03   0.000000000E+00
       20  -0.590131655E-05   0.000000000E+00  -0.256602063E-01   0.000000000E+00  -0.861064754E-03   0.000000000E+00
$MODE           3
  0.11568397E+00    0.10000000E+01
        1   0.263429112E-05   0.000000000E+00  -0.576067672E-01   0.000000000E+00  -0.158799367E-01   0.000000000E+00
        2   0.263429106E-05   0.000000000E+00  -0.523687351E-01   0.000000000E+00  -0.158798715E-01   0.000000000E+00
        3   0.263429102E-05   0.000000000E+00  -0.471307271E-01   0.000000000E+00  -0.158797988E-01   0.000000000E+00
        4   0.263429067E-05   0.000000000E+00  -0.418927506E-01   0.000000000E+00  -0.158796803E-01   0.000000000E+00
        5   0.263429025E-05   0.000000000E+00  -0.366548139E-01   0.000000000E+00  -0.158795665E-01   0.000000000E+00
        6   0.263428940E-05   0.000000000E+00  -0.314169139E-01   0.000000000E+00  -0.158794752E-01   0.000000000E+00
        7   0.263428808E-05   0.000000000E+00  -0.261790343E-01   0.000000000E+00  -0.158794381E-01   0.000000000E+00
        8   0.263428628E-05   0.000000000E+00  -0.209411598E-01   0.000000000E+00  -0.158794638E-01   0.000000000E+00
        9   0.263428372E-05   0.000000000E+00  -0.157032639E-01   0.000000000E+00  -0.158795283E-01   0.000000000E+00
       10   0.263428040E-05   0.000000000E+00  -0.104653482E-01   0.000000000E+00  -0.158795970E-01   0.000000000E+00
       11   0.263427658E-05   0.000000000E+00  -0.522741415E-02   0.000000000E+00  -0.158796378E-01   0.000000000E+00
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      12   0.263427228E-05   0.000000000E+00   0.105274241E-04   0.000000000E+00  -0.158796414E-01   0.000000000E+00
      13   0.263426748E-05   0.000000000E+00   0.524846637E-02   0.000000000E+00  -0.158795985E-01   0.000000000E+00
      14   0.263426246E-05   0.000000000E+00   0.104863755E-01   0.000000000E+00  -0.158795094E-01   0.000000000E+00
      15   0.263425736E-05   0.000000000E+00   0.157242531E-01   0.000000000E+00  -0.158793830E-01   0.000000000E+00
      16   0.263425218E-05   0.000000000E+00   0.209620807E-01   0.000000000E+00  -0.158791592E-01   0.000000000E+00
      17   0.263424892E-05   0.000000000E+00   0.261998071E-01   0.000000000E+00  -0.158788363E-01   0.000000000E+00
      18   0.263424675E-05   0.000000000E+00   0.314374643E-01   0.000000000E+00  -0.158787404E-01   0.000000000E+00
      19   0.263424598E-05   0.000000000E+00   0.366751062E-01   0.000000000E+00  -0.158787379E-01   0.000000000E+00
      20   0.263424238E-05   0.000000000E+00   0.419127512E-01   0.000000000E+00  -0.158787484E-01   0.000000000E+00
$MODE        4
  0.12029574E+02     0.10000000E+01
       1   0.964906826E-10   0.000000000E+00   0.840124977E-01   0.000000000E+00   0.490409242E-01   0.000000000E+00
       2   0.964664986E-10   0.000000000E+00   0.679688411E-01   0.000000000E+00   0.478347277E-01   0.000000000E+00
       3   0.963688526E-10   0.000000000E+00   0.523760494E-01   0.000000000E+00   0.463744401E-01   0.000000000E+00
       4   0.961657482E-10   0.000000000E+00   0.373023769E-01   0.000000000E+00   0.447728358E-01   0.000000000E+00
       5   0.958241807E-10   0.000000000E+00   0.228399398E-01   0.000000000E+00   0.426867590E-01   0.000000000E+00
       6   0.953227208E-10   0.000000000E+00   0.920851840E-02   0.000000000E+00   0.397296335E-01   0.000000000E+00
       7   0.946450444E-10   0.000000000E+00  -0.326712114E-02   0.000000000E+00   0.356797776E-01   0.000000000E+00
       8   0.937789716E-10   0.000000000E+00  -0.141867277E-01   0.000000000E+00   0.303044584E-01   0.000000000E+00
       9   0.927239588E-10   0.000000000E+00  -0.231207738E-01   0.000000000E+00   0.236707850E-01   0.000000000E+00
      10   0.914820785E-10   0.000000000E+00  -0.296902770E-01   0.000000000E+00   0.160166804E-01   0.000000000E+00
      11   0.900559105E-10   0.000000000E+00  -0.336118902E-01   0.000000000E+00   0.767889728E-02   0.000000000E+00
      12   0.884482921E-10   0.000000000E+00  -0.347252917E-01   0.000000000E+00  -0.938953964E-03   0.000000000E+00
      13   0.866625302E-10   0.000000000E+00  -0.330095688E-01   0.000000000E+00  -0.940116352E-02   0.000000000E+00
      14   0.847021141E-10   0.000000000E+00  -0.285879038E-01   0.000000000E+00  -0.172757883E-01   0.000000000E+00
      15   0.823218006E-10   0.000000000E+00  -0.217204306E-01   0.000000000E+00  -0.241701020E-01   0.000000000E+00
      16   0.813811565E-10   0.000000000E+00  -0.124190210E-01   0.000000000E+00  -0.318981230E-01   0.000000000E+00
      17   0.813434078E-10   0.000000000E+00  -0.453939923E-03   0.000000000E+00  -0.401316382E-01   0.000000000E+00
      18   0.812431433E-10   0.000000000E+00   0.132361151E-01   0.000000000E+00  -0.426224373E-01   0.000000000E+00
      19   0.810432696E-10   0.000000000E+00   0.274166292E-01   0.000000000E+00  -0.432463852E-01   0.000000000E+00
      20   0.790250282E-10   0.000000000E+00   0.417136351E-01   0.000000000E+00  -0.433922420E-01   0.000000000E+00
$MODE        5
  0.32143455E+02     0.10000000E+01
       1   0.199871818E-10   0.000000000E+00   0.108050990E+00   0.000000000E+00   0.108405427E+00   0.000000000E+00
       2   0.199513906E-10   0.000000000E+00   0.735110336E-01   0.000000000E+00   0.973290378E-01   0.000000000E+00
       3   0.198071414E-10   0.000000000E+00   0.429865841E-01   0.000000000E+00   0.850537745E-01   0.000000000E+00
       4   0.195083016E-10   0.000000000E+00   0.166608636E-01   0.000000000E+00   0.728529219E-01   0.000000000E+00
       5   0.190094579E-10   0.000000000E+00  -0.524957251E-02   0.000000000E+00   0.587152778E-01   0.000000000E+00
       6   0.182849603E-10   0.000000000E+00  -0.218968969E-01   0.000000000E+00   0.412631890E-01   0.000000000E+00
       7   0.173200194E-10   0.000000000E+00  -0.322629299E-01   0.000000000E+00   0.210413027E-01   0.000000000E+00
       8   0.161091952E-10   0.000000000E+00  -0.356189568E-01   0.000000000E+00  -0.745847165E-03   0.000000000E+00
       9   0.146666090E-10   0.000000000E+00  -0.319140730E-01   0.000000000E+00  -0.212307101E-01   0.000000000E+00
      10   0.130130160E-10   0.000000000E+00  -0.220941673E-01   0.000000000E+00  -0.373388713E-01   0.000000000E+00
      11   0.111721895E-10   0.000000000E+00  -0.803298100E-02   0.000000000E+00  -0.466116597E-01   0.000000000E+00
      12   0.917068790E-11   0.000000000E+00   0.775343463E-02   0.000000000E+00  -0.476775830E-01   0.000000000E+00
      13   0.703731898E-11   0.000000000E+00   0.225164239E-01   0.000000000E+00  -0.405238905E-01   0.000000000E+00
      14   0.480280220E-11   0.000000000E+00   0.337350184E-01   0.000000000E+00  -0.265286060E-01   0.000000000E+00
      15   0.283745848E-11   0.000000000E+00   0.395467900E-01   0.000000000E+00  -0.825247037E-02   0.000000000E+00
      16  -0.140902184E-11   0.000000000E+00   0.378509104E-01   0.000000000E+00   0.183662741E-01   0.000000000E+00
      17  -0.600914391E-11   0.000000000E+00   0.259102665E-01   0.000000000E+00   0.529084154E-01   0.000000000E+00
      18  -0.886789818E-11   0.000000000E+00   0.625033164E-02   0.000000000E+00   0.654067384E-01   0.000000000E+00
      19  -0.970276222E-11   0.000000000E+00  -0.160292664E-01   0.000000000E+00   0.690932937E-01   0.000000000E+00
      20  -0.934700025E-11   0.000000000E+00  -0.390341700E-01   0.000000000E+00   0.700678327E-01   0.000000000E+00
$MODE        6
  0.44486765E+02     0.10000000E+01
       1   0.415391010E-01   0.000000000E+00  -0.840198079E-10   0.000000000E+00  -0.105042882E-09   0.000000000E+00
       2   0.413966492E-01   0.000000000E+00  -0.511760075E-10   0.000000000E+00  -0.885674265E-10   0.000000000E+00
       3   0.408232078E-01   0.000000000E+00  -0.242056235E-10   0.000000000E+00  -0.712494060E-10   0.000000000E+00
       4   0.396401595E-01   0.000000000E+00  -0.303548833E-11   0.000000000E+00  -0.549449893E-10   0.000000000E+00
       5   0.376808809E-01   0.000000000E+00   0.124010427E-10   0.000000000E+00  -0.372744926E-10   0.000000000E+00
       6   0.348683388E-01   0.000000000E+00   0.215301893E-10   0.000000000E+00  -0.173138866E-10   0.000000000E+00
       7   0.311817128E-01   0.000000000E+00   0.238689120E-10   0.000000000E+00   0.322321273E-11   0.000000000E+00
       8   0.266481304E-01   0.000000000E+00   0.196247767E-10   0.000000000E+00   0.218869998E-10   0.000000000E+00
       9   0.213801924E-01   0.000000000E+00   0.100286050E-10   0.000000000E+00   0.351023792E-10   0.000000000E+00
      10   0.155230781E-01   0.000000000E+00  -0.263819065E-11   0.000000000E+00   0.402102695E-10   0.000000000E+00
      11   0.923819160E-02   0.000000000E+00  -0.155337281E-10   0.000000000E+00   0.365610122E-10   0.000000000E+00
      12   0.269872670E-02   0.000000000E+00  -0.259694036E-10   0.000000000E+00   0.257406762E-10   0.000000000E+00
      13  -0.391511296E-02   0.000000000E+00  -0.321285313E-10   0.000000000E+00   0.114272145E-10   0.000000000E+00
      14  -0.104210534E-01   0.000000000E+00  -0.336118528E-10   0.000000000E+00  -0.191840324E-11   0.000000000E+00
      15  -0.166398250E-01   0.000000000E+00  -0.313656232E-10   0.000000000E+00  -0.106251903E-10   0.000000000E+00
      16  -0.228123536E-01   0.000000000E+00  -0.270701093E-10   0.000000000E+00  -0.139730055E-10   0.000000000E+00
      17  -0.288888705E-01   0.000000000E+00  -0.250077723E-10   0.000000000E+00   0.846500330E-11   0.000000000E+00
      18  -0.327192076E-01   0.000000000E+00  -0.312624952E-10   0.000000000E+00   0.293823538E-10   0.000000000E+00
      19  -0.346265852E-01   0.000000000E+00  -0.423241457E-10   0.000000000E+00   0.360884212E-10   0.000000000E+00
      20  -0.352638127E-01   0.000000000E+00  -0.544417511E-10   0.000000000E+00   0.370604333E-10   0.000000000E+00
$MODE        7
  0.60568742E+02     0.10000000E+01
       1  -0.157071915E-10   0.000000000E+00  -0.146473810E+00   0.000000000E+00  -0.231409075E+00   0.000000000E+00
       2  -0.156073325E-10   0.000000000E+00  -0.760049069E-01   0.000000000E+00  -0.178094660E+00   0.000000000E+00
       3  -0.152063543E-10   0.000000000E+00  -0.241108832E-01   0.000000000E+00  -0.125859035E+00   0.000000000E+00
       4  -0.143853589E-10   0.000000000E+00   0.108493324E-01   0.000000000E+00  -0.808556818E-01   0.000000000E+00
       5  -0.130450368E-10   0.000000000E+00   0.307425413E-01   0.000000000E+00  -0.372525420E-01   0.000000000E+00
       6  -0.111616129E-10   0.000000000E+00   0.360676504E-01   0.000000000E+00   0.535285715E-02   0.000000000E+00
       7  -0.876482203E-11   0.000000000E+00   0.282228388E-01   0.000000000E+00   0.406444638E-01   0.000000000E+00
       8  -0.592813575E-11   0.000000000E+00   0.108390402E-01   0.000000000E+00   0.616895581E-01   0.000000000E+00
       9  -0.278861588E-11   0.000000000E+00  -0.102565053E-01   0.000000000E+00   0.625658035E-01   0.000000000E+00
      10   0.493359032E-12   0.000000000E+00  -0.282080249E-01   0.000000000E+00   0.431790634E-01   0.000000000E+00
      11   0.375012347E-11   0.000000000E+00  -0.371976375E-01   0.000000000E+00   0.974679138E-02   0.000000000E+00
      12   0.681538703E-11   0.000000000E+00  -0.342561362E-01   0.000000000E+00  -0.271588246E-01   0.000000000E+00
      13   0.953243719E-11   0.000000000E+00  -0.201688244E-01   0.000000000E+00  -0.559879762E-01   0.000000000E+00
      14   0.117626185E-10   0.000000000E+00   0.824117689E-03   0.000000000E+00  -0.679432884E-01   0.000000000E+00
      15   0.135319732E-10   0.000000000E+00   0.224546034E-01   0.000000000E+00  -0.598979128E-01   0.000000000E+00
      16   0.137572527E-10   0.000000000E+00   0.371430507E-01   0.000000000E+00  -0.262051871E-01   0.000000000E+00
      17   0.136003648E-10   0.000000000E+00   0.351878011E-01   0.000000000E+00   0.392888226E-01   0.000000000E+00
      18   0.135923731E-10   0.000000000E+00   0.170226636E-01   0.000000000E+00   0.698021650E-01   0.000000000E+00
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     19   0.144028607E-10   0.000000000E+00  -0.800874209E-02   0.000000000E+00   0.804691269E-01   0.000000000E+00
     20   0.146828531E-10   0.000000000E+00  -0.352386296E-01   0.000000000E+00   0.835929802E-01   0.000000000E+00
$MODE          8
  0.91085315E+02    0.10000000E+01
      1   0.486046744E-01   0.000000000E+00  -0.615091886E-10   0.000000000E+00  -0.137958169E-09   0.000000000E+00
      2   0.479059208E-01   0.000000000E+00  -0.215781245E-10   0.000000000E+00  -0.872069459E-10   0.000000000E+00
      3   0.451180218E-01   0.000000000E+00   0.143525607E-11   0.000000000E+00  -0.443955372E-10   0.000000000E+00
      4   0.395300384E-01   0.000000000E+00   0.114391337E-10   0.000000000E+00  -0.137377312E-10   0.000000000E+00
      5   0.307691829E-01   0.000000000E+00   0.122167219E-10   0.000000000E+00   0.906685267E-11   0.000000000E+00
      6   0.191985832E-01   0.000000000E+00   0.663164912E-11   0.000000000E+00   0.233567132E-10   0.000000000E+00
      7   0.573528155E-02   0.000000000E+00  -0.187181199E-11   0.000000000E+00   0.260902843E-10   0.000000000E+00
      8  -0.834933873E-02   0.000000000E+00  -0.927113360E-11   0.000000000E+00   0.169087703E-10   0.000000000E+00
      9  -0.214694297E-01   0.000000000E+00  -0.121693257E-10   0.000000000E+00  -0.683335989E-13   0.000000000E+00
     10  -0.321092880E-01   0.000000000E+00  -0.923090057E-11   0.000000000E+00  -0.169998573E-10   0.000000000E+00
     11  -0.390397742E-01   0.000000000E+00  -0.182214357E-11   0.000000000E+00  -0.260490252E-10   0.000000000E+00
     12  -0.414602554E-01   0.000000000E+00   0.664351032E-11   0.000000000E+00  -0.231802753E-10   0.000000000E+00
     13  -0.390911060E-01   0.000000000E+00   0.123567385E-10   0.000000000E+00  -0.101803897E-10   0.000000000E+00
     14  -0.322060325E-01   0.000000000E+00   0.129979194E-10   0.000000000E+00   0.613146646E-11   0.000000000E+00
     15  -0.216004107E-01   0.000000000E+00   0.895433644E-11   0.000000000E+00   0.165540121E-10   0.000000000E+00
     16  -0.768952060E-02   0.000000000E+00   0.291276007E-11   0.000000000E+00   0.183906918E-10   0.000000000E+00
     17   0.802661037E-02   0.000000000E+00  -0.121048707E-11   0.000000000E+00   0.306064256E-11   0.000000000E+00
     18   0.187754234E-01   0.000000000E+00  -0.269058856E-12   0.000000000E+00  -0.835920034E-11   0.000000000E+00
     19   0.245663136E-01   0.000000000E+00   0.315503354E-11   0.000000000E+00  -0.115919927E-10   0.000000000E+00
     20   0.265798168E-01   0.000000000E+00   0.706845509E-11   0.000000000E+00  -0.120002371E-10   0.000000000E+00
$MODE          9
  0.96043815E+02    0.10000000E+01
      1  -0.118311570E-10   0.000000000E+00  -0.190061228E+00   0.000000000E+00  -0.447342843E+00   0.000000000E+00
      2  -0.116420340E-10   0.000000000E+00  -0.616300092E-01   0.000000000E+00  -0.273393625E+00   0.000000000E+00
      3  -0.108885200E-10   0.000000000E+00   0.915922105E-02   0.000000000E+00  -0.129906339E+00   0.000000000E+00
      4  -0.938467036E-11   0.000000000E+00   0.368905308E-01   0.000000000E+00  -0.307390709E-01   0.000000000E+00
      5  -0.704655292E-11   0.000000000E+00   0.353776408E-01   0.000000000E+00   0.391381597E-01   0.000000000E+00
      6  -0.399883833E-11   0.000000000E+00   0.152167735E-01   0.000000000E+00   0.777120202E-01   0.000000000E+00
      7  -0.521845317E-12   0.000000000E+00  -0.114945238E-01   0.000000000E+00   0.772803593E-01   0.000000000E+00
      8   0.301168410E-11   0.000000000E+00  -0.317458597E-01   0.000000000E+00   0.401741901E-01   0.000000000E+00
      9   0.615838813E-11   0.000000000E+00  -0.358962654E-01   0.000000000E+00  -0.160438435E-01   0.000000000E+00
     10   0.851408638E-11   0.000000000E+00  -0.220831031E-01   0.000000000E+00  -0.638813728E-01   0.000000000E+00
     11   0.977620973E-11   0.000000000E+00   0.273416931E-02   0.000000000E+00  -0.797734440E-01   0.000000000E+00
     12   0.978262706E-11   0.000000000E+00   0.261667458E-01   0.000000000E+00  -0.558559467E-01   0.000000000E+00
     13   0.853267431E-11   0.000000000E+00   0.364970483E-01   0.000000000E+00  -0.387521114E-02   0.000000000E+00
     14   0.618673905E-11   0.000000000E+00   0.284380250E-01   0.000000000E+00   0.506997352E-01   0.000000000E+00
     15   0.307666506E-11   0.000000000E+00   0.566675410E-02   0.000000000E+00   0.814770172E-01   0.000000000E+00
     16  -0.125624964E-11   0.000000000E+00  -0.211700735E-01   0.000000000E+00   0.720839937E-01   0.000000000E+00
     17  -0.598732336E-11   0.000000000E+00  -0.331797150E-01   0.000000000E+00  -0.817119032E-02   0.000000000E+00
     18  -0.948187330E-11   0.000000000E+00  -0.217586392E-01   0.000000000E+00  -0.615052754E-01   0.000000000E+00
     19  -0.125202160E-10   0.000000000E+00   0.262655711E-02   0.000000000E+00  -0.836303031E-01   0.000000000E+00
     20  -0.133506200E-10   0.000000000E+00   0.317694569E-01   0.000000000E+00  -0.907118081E-01   0.000000000E+00
$MODE         10
  0.13745102E+03    0.10000000E+01
      1  -0.246574144E-10   0.000000000E+00  -0.211240645E+00   0.000000000E+00  -0.703891609E+00   0.000000000E+00
      2  -0.238501994E-10   0.000000000E+00  -0.225982289E-01   0.000000000E+00  -0.307917874E+00   0.000000000E+00
      3  -0.206778819E-10   0.000000000E+00   0.423576344E-01   0.000000000E+00  -0.497547363E-01   0.000000000E+00
      4  -0.146320296E-10   0.000000000E+00   0.383106762E-01   0.000000000E+00   0.727769033E-01   0.000000000E+00
      5  -0.606183786E-11   0.000000000E+00   0.671915168E-02   0.000000000E+00   0.106761986E+00   0.000000000E+00
      6   0.351785649E-11   0.000000000E+00  -0.244010324E-01   0.000000000E+00   0.703426600E-01   0.000000000E+00
      7   0.119535875E-10   0.000000000E+00  -0.355937659E-01   0.000000000E+00  -0.636596109E-02   0.000000000E+00
      8   0.172242595E-10   0.000000000E+00  -0.210619130E-01   0.000000000E+00  -0.757297929E-01   0.000000000E+00
      9   0.179637550E-10   0.000000000E+00   0.846936050E-02   0.000000000E+00  -0.914677846E-01   0.000000000E+00
     10   0.139775500E-10   0.000000000E+00   0.322310864E-01   0.000000000E+00  -0.430974136E-01   0.000000000E+00
     11   0.631432870E-11   0.000000000E+00   0.335773669E-01   0.000000000E+00   0.355007295E-01   0.000000000E+00
     12  -0.301004722E-11   0.000000000E+00   0.115107659E-01   0.000000000E+00   0.895453077E-01   0.000000000E+00
     13  -0.115425690E-10   0.000000000E+00  -0.186696566E-01   0.000000000E+00   0.815032575E-01   0.000000000E+00
     14  -0.170385168E-10   0.000000000E+00  -0.360861060E-01   0.000000000E+00   0.173339658E-01   0.000000000E+00
     15  -0.180790047E-10   0.000000000E+00  -0.289453280E-01   0.000000000E+00  -0.573819796E-01   0.000000000E+00
     16  -0.124411695E-10   0.000000000E+00  -0.238405268E-03   0.000000000E+00  -0.101478865E+00   0.000000000E+00
     17  -0.317168047E-11   0.000000000E+00   0.255630130E-01   0.000000000E+00  -0.327928255E-01   0.000000000E+00
     18   0.470419848E-11   0.000000000E+00   0.240043415E-01   0.000000000E+00   0.468674461E-01   0.000000000E+00
     19   0.113506740E-10   0.000000000E+00   0.134899950E-02   0.000000000E+00   0.863832671E-01   0.000000000E+00
     20   0.134787415E-10   0.000000000E+00  -0.301739843E-01   0.000000000E+00   0.100158763E+00   0.000000000E+00
$MODE         11
  0.14015957E+03    0.10000000E+01
      1  -0.576291542E-01   0.000000000E+00   0.980725269E-10   0.000000000E+00   0.333242682E-09   0.000000000E+00
      2  -0.556674342E-01   0.000000000E+00   0.915710684E-11   0.000000000E+00   0.142236436E-09   0.000000000E+00
      3  -0.479663635E-01   0.000000000E+00  -0.203000887E-10   0.000000000E+00   0.196413091E-10   0.000000000E+00
      4  -0.333434330E-01   0.000000000E+00  -0.172936900E-10   0.000000000E+00  -0.366727253E-10   0.000000000E+00
      5  -0.127725064E-01   0.000000000E+00  -0.199744418E-11   0.000000000E+00  -0.501725289E-10   0.000000000E+00
      6   0.991298862E-02   0.000000000E+00   0.121848098E-10   0.000000000E+00  -0.304458686E-10   0.000000000E+00
      7   0.293789839E-01   0.000000000E+00   0.163587104E-10   0.000000000E+00   0.659049826E-11   0.000000000E+00
      8   0.407627449E-01   0.000000000E+00   0.851681997E-11   0.000000000E+00   0.376644694E-10   0.000000000E+00
      9   0.409963232E-01   0.000000000E+00  -0.550707781E-11   0.000000000E+00   0.416219107E-10   0.000000000E+00
     10   0.300158201E-01   0.000000000E+00  -0.156767713E-10   0.000000000E+00   0.158738949E-10   0.000000000E+00
     11   0.108248340E-01   0.000000000E+00  -0.147259636E-10   0.000000000E+00  -0.212766396E-10   0.000000000E+00
     12  -0.113271610E-01   0.000000000E+00  -0.328217995E-11   0.000000000E+00  -0.435006629E-10   0.000000000E+00
     13  -0.303807559E-01   0.000000000E+00   0.106165107E-10   0.000000000E+00  -0.352212832E-10   0.000000000E+00
     14  -0.411240236E-01   0.000000000E+00   0.173048815E-10   0.000000000E+00  -0.286157598E-11   0.000000000E+00
     15  -0.406183041E-01   0.000000000E+00   0.126151584E-10   0.000000000E+00   0.284597181E-10   0.000000000E+00
     16  -0.286052067E-01   0.000000000E+00   0.648870766E-13   0.000000000E+00   0.414527431E-10   0.000000000E+00
     17  -0.884350721E-02   0.000000000E+00  -0.977004608E-11   0.000000000E+00   0.105932084E-10   0.000000000E+00
     18   0.733984027E-02   0.000000000E+00  -0.876257858E-11   0.000000000E+00  -0.173007938E-10   0.000000000E+00
     19   0.175849757E-01   0.000000000E+00  -0.817496843E-12   0.000000000E+00  -0.294238969E-10   0.000000000E+00
     20   0.214286212E-01   0.000000000E+00   0.975524492E-11   0.000000000E+00  -0.333674641E-10   0.000000000E+00
$MODE         12
  0.18549657E+03    0.10000000E+01
      1  -0.404638507E-10   0.000000000E+00  -0.201509387E+00   0.000000000E+00  -0.919062790E+00   0.000000000E+00
      2  -0.380511930E-10   0.000000000E+00   0.260030227E-01   0.000000000E+00  -0.231102444E+00   0.000000000E+00
      3  -0.287813835E-10   0.000000000E+00   0.528310696E-01   0.000000000E+00   0.882162354E-01   0.000000000E+00
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     4  -0.124550558E-10   0.000000000E+00   0.103583327E-01   0.000000000E+00   0.144242441E+00   0.000000000E+00
     5   0.700349952E-11   0.000000000E+00  -0.286319824E-01   0.000000000E+00   0.718209970E-01   0.000000000E+00
     6   0.223093093E-10   0.000000000E+00  -0.337885403E-01   0.000000000E+00  -0.426620603E-01   0.000000000E+00
     7   0.267462480E-10   0.000000000E+00  -0.644849833E-02   0.000000000E+00  -0.108138426E+00   0.000000000E+00
     8   0.183747313E-10   0.000000000E+00   0.266180697E-01   0.000000000E+00  -0.742932677E-01   0.000000000E+00
     9   0.119949323E-11   0.000000000E+00   0.350849221E-01   0.000000000E+00   0.275657554E-01   0.000000000E+00
    10  -0.165504652E-10   0.000000000E+00   0.112403409E-01   0.000000000E+00   0.103890459E+00   0.000000000E+00
    11  -0.263707108E-10   0.000000000E+00  -0.229223128E-01   0.000000000E+00   0.844470314E-01   0.000000000E+00
    12  -0.235562509E-10   0.000000000E+00  -0.358873191E-01   0.000000000E+00  -0.130534743E-01   0.000000000E+00
    13  -0.945550873E-11   0.000000000E+00  -0.155317805E-01   0.000000000E+00  -0.994497062E-01   0.000000000E+00
    14   0.917557331E-11   0.000000000E+00   0.199277637E-01   0.000000000E+00  -0.967849148E-01   0.000000000E+00
    15   0.232854759E-10   0.000000000E+00   0.392581119E-01   0.000000000E+00  -0.117238642E-01   0.000000000E+00
    16   0.243752766E-10   0.000000000E+00   0.225861810E-01   0.000000000E+00   0.983544682E-01   0.000000000E+00
    17   0.145431683E-10   0.000000000E+00  -0.131395540E-01   0.000000000E+00   0.797819963E-01   0.000000000E+00
    18   0.187924312E-11   0.000000000E+00  -0.244277528E-01   0.000000000E+00  -0.242919674E-01   0.000000000E+00
    19  -0.113623925E-10   0.000000000E+00  -0.505771197E-02   0.000000000E+00  -0.879574032E-01   0.000000000E+00
    20  -0.164037194E-10   0.000000000E+00   0.293153727E-01   0.000000000E+00  -0.112332562E+00   0.000000000E+00
$MODE       13
  0.18866591E+03    0.10000000E+01
     1   0.635456904E-01   0.000000000E+00  -0.128079834E-09   0.000000000E+00  -0.595027517E-09   0.000000000E+00
     2   0.596262662E-01   0.000000000E+00   0.184466311E-10   0.000000000E+00  -0.142630666E-09   0.000000000E+00
     3   0.445932641E-01   0.000000000E+00   0.336042251E-10   0.000000000E+00   0.619395460E-10   0.000000000E+00
     4   0.182827976E-01   0.000000000E+00   0.520964192E-11   0.000000000E+00   0.931262188E-10   0.000000000E+00
     5  -0.126132500E-01   0.000000000E+00  -0.192533068E-10   0.000000000E+00   0.421772862E-10   0.000000000E+00
     6  -0.360622671E-01   0.000000000E+00  -0.209869909E-10   0.000000000E+00  -0.322093635E-10   0.000000000E+00
     7  -0.413893820E-01   0.000000000E+00  -0.232926801E-11   0.000000000E+00  -0.705454456E-10   0.000000000E+00
     8  -0.262178436E-01   0.000000000E+00   0.183234681E-10   0.000000000E+00  -0.432087710E-10   0.000000000E+00
     9   0.194814539E-02   0.000000000E+00   0.217658578E-10   0.000000000E+00   0.242314316E-10   0.000000000E+00
    10   0.291485491E-01   0.000000000E+00   0.483710339E-11   0.000000000E+00   0.689086061E-10   0.000000000E+00
    11   0.419019812E-01   0.000000000E+00  -0.165994622E-10   0.000000000E+00   0.490460267E-10   0.000000000E+00
    12   0.338874248E-01   0.000000000E+00  -0.224529192E-10   0.000000000E+00  -0.168914751E-10   0.000000000E+00
    13   0.907712925E-02   0.000000000E+00  -0.712224271E-11   0.000000000E+00  -0.676667245E-10   0.000000000E+00
    14  -0.202320451E-01   0.000000000E+00   0.154316753E-10   0.000000000E+00  -0.570045845E-10   0.000000000E+00
    15  -0.395135858E-01   0.000000000E+00   0.252629817E-10   0.000000000E+00   0.111229779E-11   0.000000000E+00
    16  -0.398975614E-01   0.000000000E+00   0.125320985E-10   0.000000000E+00   0.657282754E-10   0.000000000E+00
    17  -0.229669845E-01   0.000000000E+00  -0.964425189E-11   0.000000000E+00   0.458824898E-10   0.000000000E+00
    18  -0.217392360E-02   0.000000000E+00  -0.155140169E-10   0.000000000E+00  -0.168695751E-10   0.000000000E+00
    19   0.154271620E-01   0.000000000E+00  -0.339842644E-11   0.000000000E+00  -0.535861511E-10   0.000000000E+00
    20   0.228552354E-01   0.000000000E+00   0.173654672E-10   0.000000000E+00  -0.676305216E-10   0.000000000E+00
$MODE       14
  0.23272215E+03    0.10000000E+01
     1   0.629441732E-01   0.000000000E+00   0.381452117E-10   0.000000000E+00   0.223647642E-09   0.000000000E+00
     2   0.570369925E-01   0.000000000E+00  -0.130972860E-10   0.000000000E+00   0.187294540E-10   0.000000000E+00
     3   0.349998252E-01   0.000000000E+00  -0.840209429E-11   0.000000000E+00  -0.414391601E-10   0.000000000E+00
     4   0.253051461E-03   0.000000000E+00   0.441981227E-11   0.000000000E+00  -0.263159255E-10   0.000000000E+00
     5  -0.307485051E-01   0.000000000E+00   0.794513811E-11   0.000000000E+00   0.721423131E-11   0.000000000E+00
     6  -0.386506051E-01   0.000000000E+00   0.166087382E-11   0.000000000E+00   0.264532754E-10   0.000000000E+00
     7  -0.177459453E-01   0.000000000E+00  -0.617960661E-11   0.000000000E+00   0.157279450E-10   0.000000000E+00
     8   0.164587127E-01   0.000000000E+00  -0.683988368E-11   0.000000000E+00  -0.121296363E-10   0.000000000E+00
     9   0.382513236E-01   0.000000000E+00   0.290908844E-12   0.000000000E+00  -0.260831878E-10   0.000000000E+00
    10   0.311972872E-01   0.000000000E+00   0.712371065E-11   0.000000000E+00  -0.105282004E-10   0.000000000E+00
    11   0.616320528E-03   0.000000000E+00   0.592138413E-11   0.000000000E+00   0.169641350E-10   0.000000000E+00
    12  -0.304294343E-01   0.000000000E+00  -0.194812553E-11   0.000000000E+00   0.251872584E-10   0.000000000E+00
    13  -0.385273216E-01   0.000000000E+00  -0.753954195E-11   0.000000000E+00   0.469814659E-11   0.000000000E+00
    14  -0.175704640E-01   0.000000000E+00  -0.440525282E-11   0.000000000E+00  -0.216322321E-10   0.000000000E+00
    15   0.166368826E-01   0.000000000E+00   0.420566895E-11   0.000000000E+00  -0.249305757E-10   0.000000000E+00
    16   0.402391557E-01   0.000000000E+00   0.849457361E-11   0.000000000E+00   0.152034946E-11   0.000000000E+00
    17   0.389683581E-01   0.000000000E+00   0.264264466E-11   0.000000000E+00   0.252984815E-10   0.000000000E+00
    18   0.161759943E-01   0.000000000E+00  -0.340773330E-11   0.000000000E+00   0.496645049E-11   0.000000000E+00
    19  -0.164870406E-01   0.000000000E+00  -0.179292871E-11   0.000000000E+00  -0.136446403E-10   0.000000000E+00
    20  -0.326162494E-01   0.000000000E+00   0.441064323E-11   0.000000000E+00  -0.213883944E-10   0.000000000E+00
$MODE       15
  0.24109437E+03    0.10000000E+01
     1  -0.128965633E-10   0.000000000E+00   0.174376328E+00   0.000000000E+00   0.106464443E+01   0.000000000E+00
     2  -0.115975736E-10   0.000000000E+00  -0.662214216E-01   0.000000000E+00   0.589590428E-01   0.000000000E+00
     3  -0.678081910E-11   0.000000000E+00  -0.355138989E-01   0.000000000E+00  -0.207183277E+00   0.000000000E+00
     4   0.635080091E-12   0.000000000E+00   0.252304352E-01   0.000000000E+00  -0.111722142E+00   0.000000000E+00
     5   0.678992500E-11   0.000000000E+00   0.359866380E-01   0.000000000E+00   0.533108757E-01   0.000000000E+00
     6   0.753484821E-11   0.000000000E+00   0.186750973E-02   0.000000000E+00   0.128542777E+00   0.000000000E+00
     7   0.227497559E-11   0.000000000E+00  -0.324954528E-01   0.000000000E+00   0.553688494E-01   0.000000000E+00
     8  -0.480771752E-11   0.000000000E+00  -0.280230460E-01   0.000000000E+00  -0.789625936E-01   0.000000000E+00
     9  -0.799913295E-11   0.000000000E+00   0.938053712E-02   0.000000000E+00  -0.120379743E+00   0.000000000E+00
    10  -0.471632615E-11   0.000000000E+00   0.359262969E-01   0.000000000E+00  -0.211365652E-01   0.000000000E+00
    11   0.238378008E-11   0.000000000E+00   0.206170566E-01   0.000000000E+00   0.102730016E+00   0.000000000E+00
    12   0.755457792E-11   0.000000000E+00  -0.186299703E-01   0.000000000E+00   0.106404988E+00   0.000000000E+00
    13   0.661101344E-11   0.000000000E+00  -0.358040402E-01   0.000000000E+00  -0.152009527E-01   0.000000000E+00
    14   0.316764311E-12   0.000000000E+00  -0.101557245E-01   0.000000000E+00  -0.122674731E+00   0.000000000E+00
    15  -0.652850854E-11   0.000000000E+00   0.306289516E-01   0.000000000E+00  -0.983074011E-01   0.000000000E+00
    16  -0.104800683E-10   0.000000000E+00   0.390623823E-01   0.000000000E+00   0.486143128E-01   0.000000000E+00
    17  -0.862821076E-11   0.000000000E+00   0.296745791E-02   0.000000000E+00   0.121241840E+00   0.000000000E+00
    18  -0.218104947E-11   0.000000000E+00  -0.224647857E-01   0.000000000E+00   0.691695211E-02   0.000000000E+00
    19   0.276990111E-11   0.000000000E+00  -0.872605313E-02   0.000000000E+00  -0.854280070E-01   0.000000000E+00
    20   0.597666417E-11   0.000000000E+00   0.281462488E-01   0.000000000E+00  -0.124962539E+00   0.000000000E+00
$MODE       16
  0.26795948E+03    0.10000000E+01
     1   0.602908611E-01   0.000000000E+00   0.730095316E-11   0.000000000E+00   0.504949754E-10   0.000000000E+00
     2   0.527895178E-01   0.000000000E+00  -0.360892840E-11   0.000000000E+00  -0.170562411E-11   0.000000000E+00
     3   0.255533062E-01   0.000000000E+00  -0.977328933E-12   0.000000000E+00  -0.107301965E-10   0.000000000E+00
     4  -0.128886269E-01   0.000000000E+00   0.166468632E-11   0.000000000E+00  -0.284279312E-11   0.000000000E+00
     5  -0.362865813E-01   0.000000000E+00   0.124893102E-11   0.000000000E+00   0.499090766E-11   0.000000000E+00
     6  -0.249030456E-01   0.000000000E+00  -0.744430537E-12   0.000000000E+00   0.546657819E-11   0.000000000E+00
     7   0.106413916E-01   0.000000000E+00  -0.165049698E-11   0.000000000E+00  -0.691230242E-12   0.000000000E+00
     8   0.354565709E-01   0.000000000E+00  -0.406355382E-12   0.000000000E+00  -0.581057073E-11   0.000000000E+00
     9   0.248224140E-01   0.000000000E+00   0.135938201E-11   0.000000000E+00  -0.343523969E-11   0.000000000E+00
    10  -0.106290889E-01   0.000000000E+00   0.137350332E-11   0.000000000E+00   0.335336909E-11   0.000000000E+00
```

```
      11  -0.354536745E-01   0.000000000E+00  -0.379501097E-12   0.000000000E+00   0.583453557E-11   0.000000000E+00
      12  -0.248318288E-01   0.000000000E+00  -0.166070661E-11   0.000000000E+00   0.899303906E-12   0.000000000E+00
      13   0.106168102E-01   0.000000000E+00  -0.862482353E-12   0.000000000E+00  -0.501725591E-11   0.000000000E+00
      14   0.354507620E-01   0.000000000E+00   0.946757565E-12   0.000000000E+00  -0.455557497E-11   0.000000000E+00
      15   0.248412319E-01   0.000000000E+00   0.144090469E-11   0.000000000E+00   0.225205972E-11   0.000000000E+00
      16  -0.121424675E-01   0.000000000E+00  -0.549016461E-12   0.000000000E+00   0.743323508E-11   0.000000000E+00
      17  -0.412071811E-01   0.000000000E+00  -0.181389226E-11   0.000000000E+00  -0.190286052E-11   0.000000000E+00
      18  -0.317051694E-01   0.000000000E+00  -0.489581826E-12   0.000000000E+00  -0.440140522E-11   0.000000000E+00
      19   0.142055207E-01   0.000000000E+00   0.793317129E-12   0.000000000E+00  -0.359385194E-11   0.000000000E+00
      20   0.412476863E-01   0.000000000E+00   0.196193732E-11   0.000000000E+00  -0.351739795E-11   0.000000000E+00
$MODE       17
  0.30274189E+03    0.10000000E+01
       1   0.678914109E-01   0.000000000E+00  -0.242836547E-10   0.000000000E+00  -0.193735907E-09   0.000000000E+00
       2   0.571091667E-01   0.000000000E+00   0.153328053E-10   0.000000000E+00   0.271708447E-10   0.000000000E+00
       3   0.191703626E-01   0.000000000E+00   0.219952386E-12   0.000000000E+00   0.414001045E-10   0.000000000E+00
       4  -0.272981552E-01   0.000000000E+00  -0.753557041E-11   0.000000000E+00  -0.269515625E-11   0.000000000E+00
       5  -0.395507567E-01   0.000000000E+00  -0.175638377E-11   0.000000000E+00  -0.266985746E-10   0.000000000E+00
       6  -0.451088286E-02   0.000000000E+00   0.568658078E-11   0.000000000E+00  -0.114895782E-10   0.000000000E+00
       7   0.353186265E-01   0.000000000E+00   0.445836376E-11   0.000000000E+00   0.177196561E-10   0.000000000E+00
       8   0.300240927E-01   0.000000000E+00  -0.317578892E-11   0.000000000E+00   0.213470800E-10   0.000000000E+00
       9  -0.135871719E-01   0.000000000E+00  -0.628072161E-11   0.000000000E+00  -0.545993891E-11   0.000000000E+00
      10  -0.398584769E-01   0.000000000E+00  -0.427459359E-12   0.000000000E+00  -0.245057174E-10   0.000000000E+00
      11  -0.152624755E-01   0.000000000E+00   0.604546871E-11   0.000000000E+00  -0.864209259E-11.  0.000000000E+00
      12   0.288114658E-01   0.000000000E+00   0.393373653E-11   0.000000000E+00   0.194185528E-10   0.000000000E+00
      13   0.361162672E-01   0.000000000E+00  -0.367574057E-11   0.000000000E+00   0.193849955E-10   0.000000000E+00
      14  -0.267041190E-02   0.000000000E+00  -0.575036263E-11   0.000000000E+00  -0.884793895E-11   0.000000000E+00
      15  -0.380491465E-01   0.000000000E+00   0.108629456E-11   0.000000000E+00  -0.272628822E-10   0.000000000E+00
      16  -0.257182729E-01   0.000000000E+00   0.835145739E-11   0.000000000E+00  -0.981592811E-11   0.000000000E+00
      17   0.163077765E-01   0.000000000E+00   0.431622863E-11   0.000000000E+00   0.284897279E-10   0.000000000E+00
      18   0.314095494E-01   0.000000000E+00  -0.369399397E-11   0.000000000E+00   0.107854254E-10   0.000000000E+00
      19  -0.539753052E-02   0.000000000E+00  -0.324926132E-11   0.000000000E+00  -0.129681227E-10   0.000000000E+00
      20  -0.330836428E-01   0.000000000E+00   0.350574488E-11   0.000000000E+00  -0.242343211E-10   0.000000000E+00
$MODE       18
  0.30414468E+03    0.10000000E+01
       1  -0.114110200E-10   0.000000000E+00  -0.136579397E+00   0.000000000E+00  -0.109550701E+01   0.000000000E+00
       2  -0.958194820E-11   0.000000000E+00   0.869411842E-01   0.000000000E+00   0.158070589E+00   0.000000000E+00
       3  -0.315484076E-11   0.000000000E+00   0.449925024E-03   0.000000000E+00   0.233643471E+00   0.000000000E+00
       4   0.466571232E-11   0.000000000E+00  -0.427691843E-01   0.000000000E+00  -0.183148292E-01   0.000000000E+00
       5   0.660582078E-11   0.000000000E+00  -0.923623327E-02   0.000000000E+00  -0.151999977E+00   0.000000000E+00
       6   0.580500229E-12   0.000000000E+00   0.325968338E-01   0.000000000E+00  -0.624248959E-01   0.000000000E+00
       7  -0.603067412E-11   0.000000000E+00   0.245868805E-01   0.000000000E+00   0.103011886E+00   0.000000000E+00
       8  -0.486608707E-11   0.000000000E+00  -0.188686097E-01   0.000000000E+00   0.119226742E+00   0.000000000E+00
       9   0.256628217E-11   0.000000000E+00  -0.353127679E-01   0.000000000E+00  -0.351316561E-01   0.000000000E+00
      10   0.669312808E-11   0.000000000E+00  -0.121861749E-02   0.000000000E+00  -0.139226880E+00   0.000000000E+00
      11   0.219889376E-11   0.000000000E+00   0.346378867E-01   0.000000000E+00  -0.441617480E-01   0.000000000E+00
      12  -0.512764206E-11   0.000000000E+00   0.209938906E-01   0.000000000E+00   0.113851201E+00   0.000000000E+00
      13  -0.584957288E-11   0.000000000E+00  -0.224602545E-01   0.000000000E+00   0.108064005E+00   0.000000000E+00
      14   0.963119406E-12   0.000000000E+00  -0.329435777E-01   0.000000000E+00  -0.555464437E-01   0.000000000E+00
      15   0.619306086E-11   0.000000000E+00   0.670781103E-02   0.000000000E+00  -0.151161485E+00   0.000000000E+00
      16   0.270256080E-11   0.000000000E+00   0.439705572E-01   0.000000000E+00  -0.403912630E-01   0.000000000E+00
      17  -0.594964533E-11   0.000000000E+00   0.197833091E-01   0.000000000E+00   0.145448225E+00   0.000000000E+00
      18  -0.637834283E-11   0.000000000E+00  -0.187101250E-01   0.000000000E+00   0.443490736E-01   0.000000000E+00
      19   0.132146968E-11   0.000000000E+00  -0.125650402E-01   0.000000000E+00  -0.802927503E-01   0.000000000E+00
      20   0.814970105E-11   0.000000000E+00   0.273769109E-01   0.000000000E+00  -0.141489568E+00   0.000000000E+00
$MODE       19
  0.34073782E+03    0.10000000E+01
       1  -0.707538826E-01   0.000000000E+00   0.286928532E-12   0.000000000E+00   0.262347720E-11   0.000000000E+00
       2  -0.565194476E-01   0.000000000E+00  -0.221984002E-12   0.000000000E+00  -0.690287092E-12   0.000000000E+00
       3  -0.840091489E-02   0.000000000E+00   0.480007977E-13   0.000000000E+00  -0.495289349E-12   0.000000000E+00
       4   0.394299547E-01   0.000000000E+00   0.105439962E-12   0.000000000E+00   0.235797171E-12   0.000000000E+00
       5   0.288337445E-01   0.000000000E+00  -0.219086549E-13   0.000000000E+00   0.399183609E-12   0.000000000E+00
       6  -0.242519715E-01   0.000000000E+00  -0.938925746E-13   0.000000000E+00  -0.298463827E-13   0.000000000E+00
       7  -0.375458217E-01   0.000000000E+00  -0.115502451E-13   0.000000000E+00  -0.367137329E-12   0.000000000E+00
       8   0.980588267E-02   0.000000000E+00   0.869057320E-13   0.000000000E+00  -0.124434647E-12   0.000000000E+00
       9   0.413050297E-01   0.000000000E+00   0.469408709E-13   0.000000000E+00   0.322686439E-12   0.000000000E+00
      10   0.602871042E-02   0.000000000E+00  -0.675104098E-13   0.000000000E+00   0.247050254E-12   0.000000000E+00
      11  -0.389938711E-01   0.000000000E+00  -0.712141591E-13   0.000000000E+00  -0.237902197E-12   0.000000000E+00
      12  -0.209773503E-01   0.000000000E+00   0.541938680E-13   0.000000000E+00  -0.403252596E-12   0.000000000E+00
      13   0.309520756E-01   0.000000000E+00   0.149909210E-12   0.000000000E+00  -0.172574001E-12   0.000000000E+00
      14   0.328430569E-01   0.000000000E+00   0.122588716E-12   0.000000000E+00   0.472429997E-12   0.000000000E+00
      15  -0.183613752E-01   0.000000000E+00  -0.103128223E-12   0.000000000E+00   0.583827601E-12   0.000000000E+00
      16  -0.424328354E-01   0.000000000E+00  -0.503939203E-13   0.000000000E+00  -0.107313464E-11   0.000000000E+00
      17  -0.811679272E-02   0.000000000E+00   0.242277663E-12   0.000000000E+00   0.105857230E-11   0.000000000E+00
      18   0.266238962E-01   0.000000000E+00  -0.370053959E-12   0.000000000E+00   0.164557042E-11   0.000000000E+00
      19   0.161849488E-02   0.000000000E+00  -0.771139226E-12   0.000000000E+00   0.103414361E-11   0.000000000E+00
      20  -0.269328262E-01   0.000000000E+00  -0.112669386E-11   0.000000000E+00   0.109978557E-11   0.000000000E+00
$MODE       20
  0.37463267E+03    0.10000000E+01
       1  -0.355947090E-11   0.000000000E+00   0.958891159E-01   0.000000000E+00   0.995287908E+00   0.000000000E+00
       2  -0.269382803E-11   0.000000000E+00  -0.855826082E-01   0.000000000E+00  -0.340053935E+00   0.000000000E+00
       3   0.113863383E-12   0.000000000E+00   0.332714032E-01   0.000000000E+00  -0.148576036E+00   0.000000000E+00
       4   0.225867224E-11   0.000000000E+00   0.320750366E-01   0.000000000E+00   0.154238522E+00   0.000000000E+00
       5   0.488809278E-12   0.000000000E+00  -0.248642677E-01   0.000000000E+00   0.120952523E+00   0.000000000E+00
       6  -0.206780838E-11   0.000000000E+00  -0.303011707E-01   0.000000000E+00  -0.938110068E-01   0.000000000E+00
       7  -0.594716624E-12   0.000000000E+00   0.170112184E-01   0.000000000E+00  -0.136577282E+00   0.000000000E+00
       8   0.203444028E-11   0.000000000E+00   0.345172400E-01   0.000000000E+00   0.512864949E-01   0.000000000E+00
       9   0.687752556E-12   0.000000000E+00  -0.711062651E-02   0.000000000E+00   0.150819297E+00   0.000000000E+00
      10  -0.200299372E-11   0.000000000E+00  -0.366317617E-01   0.000000000E+00  -0.746299547E-02   0.000000000E+00
      11  -0.779376076E-12   0.000000000E+00  -0.358257357E-02   0.000000000E+00  -0.153054996E+00   0.000000000E+00
      12   0.196727405E-11   0.000000000E+00   0.356003830E-01   0.000000000E+00  -0.372691834E-01   0.000000000E+00
      13   0.869093832E-12   0.000000000E+00   0.140355313E-01   0.000000000E+00   0.141894644E+00   0.000000000E+00
      14  -0.192748717E-11   0.000000000E+00  -0.312268376E-01   0.000000000E+00   0.774851990E-01   0.000000000E+00
      15  -0.116408916E-11   0.000000000E+00  -0.219896528E-01   0.000000000E+00  -0.124185553E+00   0.000000000E+00
      16   0.272999754E-11   0.000000000E+00   0.343504652E-01   0.000000000E+00  -0.144112587E+00   0.000000000E+00
      17   0.341732276E-12   0.000000000E+00   0.346565590E-01   0.000000000E+00   0.140226171E+00   0.000000000E+00
```

```
18  -0.142483334E-11   0.000000000E+00  -0.131227186E-01   0.000000000E+00   0.864021047E-01   0.000000000E+00
19  -0.653929602E-12   0.000000000E+00  -0.168075647E-01   0.000000000E+00  -0.719059785E-01   0.000000000E+00
20   0.323921072E-11   0.000000000E+00   0.271864737E-01   0.000000000E+00  -0.164110128E+00   0.000000000E+00
```

Listing 9.7.4 Output of Mass change due to Structure: masschng.dat

```
0.00000000          0.11994028E+00
0.32985264          0.27478981E+00
0.65970528          0.34499741E+00
0.98955792          0.40436554E+00
1.31941056          0.44068909E+00
1.64926314          0.45864868E+00
1.97911584          0.46505737E+00
2.30896831          0.46575165E+00
2.63882113          0.46575165E+00
2.96867371          0.46575165E+00
3.29852629          0.46575165E+00
3.62837887          0.46575165E+00
3.95823169          0.46575165E+00
4.28808403          0.46575165E+00
4.61793661          0.45078278E+00
4.94778967          0.42084122E+00
5.27764225          0.48175430E+00
5.60749483          0.63463593E+00
5.93734741          0.71089172E+00
6.26719999          0.35507202E+00
```

9.8 Run UCDA to get TRIM and ASE solution

This section corresponds to the Step 6 in the Graphical User Interface (GUI). See Figure 9.8.1 below.

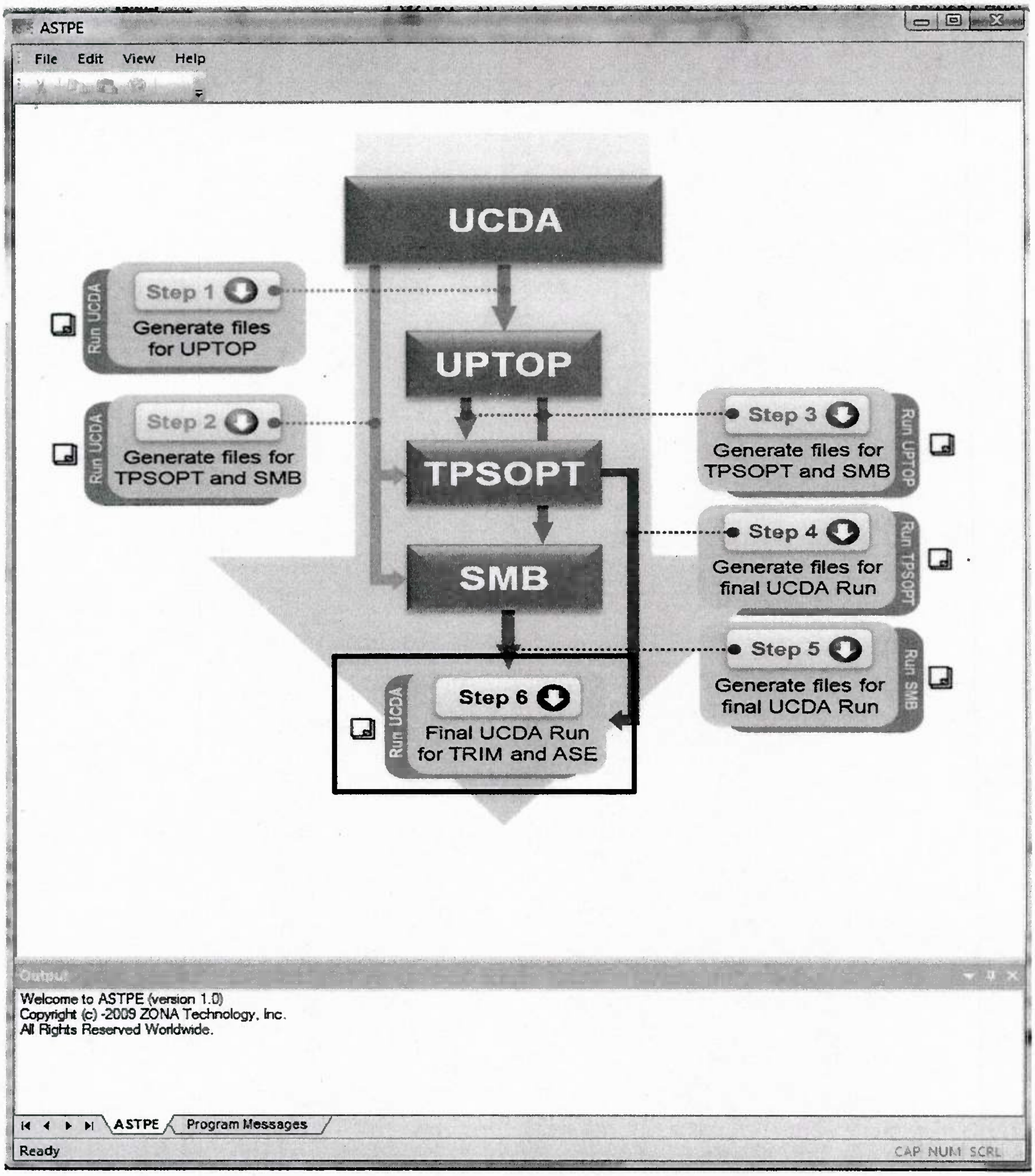


Figure 9.8.1 Section Corresponding to Step 6 of GUI

Input Files:

File Name	Type	Remarks	See Listing
vehicle.inp	Standard input file	Also look at Table 9.8.1	Shown in Listing 9.8.1
chem.bin	Engine chemistry information	Required	Shown in Listing 9.2.2
SEDvehicle.inp	Standard input file for SED type vehicle	Required	Shown in Listing 9.2.3
mass_tps.dat	Generated by TPSOPT	ifeedback needs to be 1	Shown in Listing 9.8.2
masschng.dat	Generated by SMB	ifeedback needs to be 1	Shown in Listing 9.8.3
RDOF_EIGEN.FREE	Generated by SMB	ifeedback needs to be 1	Shown in Listing 9.8.4

Output Files:

File Name	Type	Remarks	See Listing
trim_output.dat	Trim results by UCDA	See Fig. 9.8.2	Shown in Listing 9.8.5
Prep_ASE.dat	ASE results by UCDA	See Tables 9.8.2-9.8.3	Shown in Listing 9.8.6

Input File Descriptions

vehicle.inp: See Listing 9.8.1 for the entire input file. Also, Table 9.8.1 shows the necessary block and change in input parameters therein. The user should turn on **itrim** so that UCDA includes control surface in its calculation. **ideriv** is the input switch parameter that is to be set to **1** for running TRIM and ASE. **itps** should be turned back to **0** so that TPS geometry information is not created and in the process that saves some computational run time. Finally, **ifeedback** should be turned on to include the mass update from TPS and SMB. The user should note at this point that before this step, **ifeedback** was always set to **0**. That is because before this step, TPSOPT and SMB was never run (look at Figure 9.8.1). This step finishes one design cycle. After this step, for all the subsequent design cycles, this **ifeedback** parameter should ALWAYS be set to **1**. The code internally keeps track of the mass for each design cycle and that needs **ifeedback** to be set to **1**. If **ifeedback** value is set to **0** by mistake, the mass information is not going to be right.

Table 9.8.1: Showing Necessary Block on Vehicle.inp to Compute TRIM and ASE

TEST INPUT DECK: Note - this line must be here!	
2	ialtdyn - Inlet specified alt. (0), Fixed alt. (1), or Fixed dyn. press. (2)
1	ithrottle - Run engine as a function of: (0) equivalence ratio, (1) % throttle
1	iunits - Output unit switch: SI (1) or English (2)
3	ivisc - Viscous flag: inviscid (1), laminar (2), transitional (3), turbulent (4)
1	iequiv - find max equiv ratio for choked flow: off (0) -> single run, on (1)
2	inozorder - Nozzle polynomial order: 1st (flat plate) -> 3rd
1	iheight - Height constrained vehicle: no (0) = linlet set, yes (1) = height set
0	itrajectory - Run multiple trajectory points: no (0), discrete (1), matrix (2)
0	icone - cone flow data: exact (0), curve-fit approximation (1)
4	imodel - Forebody type: WA (1), VWA (2), or VWA + cone flow (3)
1	itrim - Control surface deflection to trim the vehicle: no (0), yes (1), or optimize (2)
1	ideriv - Calculate derivatives: no (0), yes (1)
0	itps - If itps is 1, then prepare for tps and smb. ideriv and itps cannot be 1 at one time
1	ifeedback - If 1, then gets weight and Cg information from SMB and TPSOPT

chem.bin: This file does not change for any UCDA run. Please see Section 9.2 for description on this file.

mass_tps.dat: This file is shown in Listing 9.8.2. It is generated by TPSOPT run. More on this can be found in Section 6.

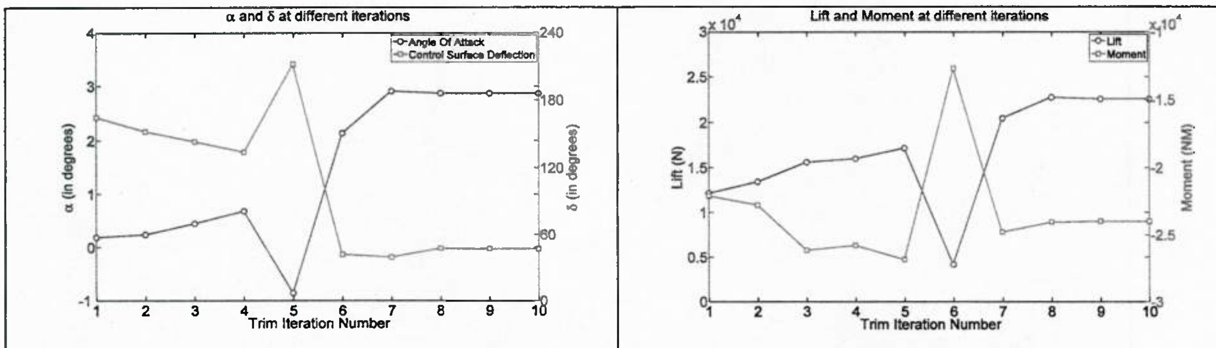
masschng.dat: This file is shown in Listing 9.8.3 and it is generated by SMB run. When UCDA was run to generate the geometry for TPSOPT and SMB that were described in Section 9.5, the structure was approximated by a finite number of discrete points. masschng.dat outputs the additional mass due to skin thickness at each of those points. More on this can be found in Section 9.7.

RDOF_EIGEN.DAT: This file is shown in Listing 9.8.4. It is also generated by SMB run. Natural frequencies and generalized masses of the first 20 modes are recorded in the file. More on this can be found in Section 9.7.

Output File descriptions

Trim_output.dat: This file is shown in Listing 9.8.5. It outputs the summary of information related to trim iterations. Geometric information such as C.G., reference area, reference chord and aerodynamic information such as Coefficients of lift, drag and moment due to change in angle of attack and control surface deflection angle are some of the information. Also, trim variables angle of attack and control surface deflection angles are listed for each iteration.

The iteration history from trim_output.dat file is shown in Figure 9.8.2. It can be seen that this iterative process requires only less than 10 iterations to achieve a fully converged solution. In fact, the mean flow condition in terms of α_0 and δ_0 does not change significantly after 5 iterations. Meanwhile, the lift and moment at the fifth iteration have already nearly satisfied the lift-equal-weight and zero-pitch-moment conditions. From the fifth to the tenth iteration, the trim solution remains nearly the same; indicating that this iterative process is stable and provides a fast converging rate.



(a) Mean Flow Condition	(b) Lift and Pitch Moment

Figure 9.8.2 Iteration history of the iterative process for solving the nonlinear trim problem

Prep_ASE.dat: This file is shown in Listing 9.8.6. It outputs the summary of information related to ASE matrix preparation. As shown in the listing, A and B matrices are listed first. Then, the eigenvalues of matrix A is given. Frequency and damping ratio corresponding to the eigenvalues are then output. Finally, other aerodynamic information are written out so that the results can be compared with analytical expressions.

Validation of the ASE module

The validation of the ASE module can be achieved by first excluding the elastic modes then comparing the eigenvalues of the matrix $\left[\bar{A}\right]$ to those of analytical flight dynamic equations shown in the following equations[3]:

For Phugoid mode:.

$$\omega_{np} = \frac{\rho S U \sqrt{-C_{L_u} C_{L_o}}}{2m} \tag{9.8.1}$$

$$\zeta_p = \frac{-C_{x_u}}{2\dfrac{mU}{Sq}\dfrac{\sqrt{-C_{L_u} C_L}}{mU/Sq}} = \frac{-C_{D_u}}{2\sqrt{-C_{L_u} C_{L_o}}} \tag{9.8.2}$$

For short period mode:

$$\omega = \left(\frac{\dfrac{c}{2U} C_{m_q} C_{L_\alpha} - \dfrac{mU}{Sq} C_{m_\alpha}}{\left(\dfrac{I_y}{Sqc}\right)\left(\dfrac{mU}{Sq}\right)} \right)^{1/2} \tag{9.8.3}$$

$$\zeta = -\frac{1}{4}\left(C_{m_q} + C_{m_\alpha} + \frac{2l_y}{mc^2} C_{L_\alpha} \right) \left(\frac{mc^2}{I_y \left(\dfrac{C_{m_q} C_{L_\alpha}}{2} - \dfrac{2mC_{m_\alpha}}{\rho Sc} \right)} \right)^{1/2} \tag{9.8.4}$$

The aerodynamic stability derivatives are computed first on the selected scramjet flight vehicle at the trim condition of $\alpha = 2.86°$, $\delta = 46.98°$. These aerodynamic stability derivatives are shown in

[3] Blakelock, J. H., "Automated Control of Aircraft and Missiles," Air Force Institute of Technology, 1981.

Table 9.8.2. Other parameters required by the analytical flight dynamic equations are: mass (m) = 1328.874, moment of inertia (Iy) = 18848.73, velocity (U) = 2090.866, surface area (S) = 1.829348, dynamic pressure (q) = 81396.51 and reference chord (c) = 6.267200.

Table 9.8.2 Aerodynamic Stability Derivatives of a Scramjet Flight Vehicle

Airframe State	C_D	C_L	C_M
Mean Flow	**0.1399257**	**0.1511889**	**-2.5678078E-02**
Forward Velocity	**2.9367459E-04**	**1.9072900E-04**	**-6.6151595E-05**
Angle of Attack	**2.717112**	**1.752287**	**-0.1032690**
Pitch Rate	**0.5058688**	**0.1237800**	**-4.5670047E-02**

It can be seen in Table 9.8.2 that the pitch moment stability derivative of angle of attack (C_{m_α}) is positive; indicating a statically stable flight vehicle.

Two sets of the ASE module of ASTPE are computed, one without the elastic mode (rigid body modes only) and the other with the first bending mode and compared to the analytical solution. This comparison is presented in Table 9.8.3 where an excellent agreement between the ASE module result without the elastic mode and the analytical solution can be seen. Meanwhile, the ASE module result with the first bending mode shows only a slight difference from that with only the rigid modes. This suggests that the structure designed by the SMB module provides sufficient stiffness by which the impact of aeroelastic effects on the flight dynamics is minimized.

Table 9.8.3 Validation of the ASE module with Analytical Solution

Longitudinal Dynamics	ASTPE				Analytical (Rigid)	
	+ Bending		Rigid			
	Damping	Frequency	Damping	Frequency	Damping	Frequency
ShortPeriod	0.012	0.6843 (Hz)	0.0583	0.3264 (Hz)	0.044	0.3264 (Hz)
Phugoid	-1.0	0.00114 (Hz)	-1.0	0.01145 (Hz)	-1.0	0.01145 (Hz)

Note that the negative damping of the short period mode leading to a statically unstable flight vehicle must be stabilized by a flight control system. A flight control system is designed for studied SED and is given in Figure 9.8.3.

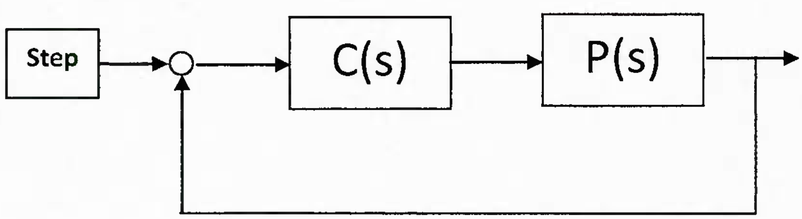


Figure 9.8.3 Block diagram of closed loop system

The compensator $C(s)$ takes the form:

$$C(s) = \frac{9297.4(s^2+0.019s+0.00018)(s^2+3.5s+5.079)(s^2-0.0045s+112.4)(s^2+0.0019s+829.4)}{s(s^2+0.01953s+0.0002)(s^2+0.00739s+110.3)(s^2+0.01718s+829.4)(s^2+79.2s+3081)}$$

Listing 9.8.1: Vehicle.inp Input File for TRIM and ASE

```
TEST INPUT DECK:  Note - this line must be here!
2        ialtdyn - Inlet specified alt. (0), Fixed alt. (1), or Fixed dyn. press. (2)
1        ithrottle - Run engine as a function of: (0) equivalence ratio, (1) % throttle, (2) max throttle
1        iunits - Output unit switch: SI (1) or English (2)
3        ivisc - Viscous flag: inviscid (1), laminar (2), transitional (3), turbulent (4)
1        iequiv - find max equiv ratio for choked flow: off (0) -> single run, on (1)
2        inozorder - Nozzle polynomial order: 1st (flat plate) -> 3rd
1        iheight - Height constrained vehicle: no (0) = linlet set, yes (1) = height set
0        itrajectory - Run multiple trajectory points: no (0), discrete (1), matrix (2)
0        icone - cone flow data: exact (0), curve-fit approximation (1)
4        imodel - Forebody type: WA (1), VWA (2), VWA + cone flow (3), or SED (4)
```

```
1        itrim - Control surface deflection to trim the vehicle: no (0), yes (1), or optimize (2)
1        ideriv - Calculate derivatives: no (0), yes (1)
0        itps - If itps is 1, then prepare for tps and smb. ideriv and itps cannot be 1 at one time
1        ifeedback - If 1, then gets weight and Cg information from SMB and TPSOPT

OUTPUT FILE SWITCHES AND NAMES:
0   'plot.dat'                         VEHICLEFIG:        off (0), select (1), x,y,z (2), all (3)
3 1 2 3 8 18 23        1st # -> # of variables to read, others -> vars to plot
0   'metrics.dat'              METRICS:  off (0), on-real (1), on-cmplx (2)
0   'cowlexit.dat'             COWLEXIT:          off (0), on (1)
0   'moc.dat'                          NOZFIG:   off (0), P,T,M (1), all (2)
0   'offdesign.dat'                    AOA:               off (0), on (1), UPTOP input tables (2), UPTOP input files (3)
0   'scramjet.dat'             CKENGINE: off (0), on (1)
0                                      IPRINTINLET:       off (0), all (1), results (2), all-real (3), results-real (4)
0                                      IPRINTENGINE:      off (0), on (1)
0                                      IDEBUG:          off (0), on (1) [print debugging info]

ZONE DATA AND GRID SIZES:
21       NUMBER OF ZONES
'forebody : top'             3         3
'keel : top'                 3         3
'aftbody : top'              3         3
'forebody : bot'             31        31
'ramps : bot'                55        6
'comb : bot'                 101       6
'cowl : top'                 101       6
'nozzle : bot'               31        6
'ramp walls : inside'        35        6
'comb wall : inside'         101       7
'nozzle wall : inside'       21        7
'aftbody : bot'              101       31
'cowl : bot'                 101       6
'ramp walls : outside'       35        6
'comb wall : outside'        101       7
'nozzle wall : outside'      21        7
'SEDbody : top'              121       46
'Control_1 : top'            31        31   (Control surface dimensions must be the same)
'Control_1 : bottom'         31        31   (Control surface dimensions must be the same)
'Control_2 : top'            31        31   (Control surface dimensions must be the same)
'Control_2 : bottom'         31        31   (Control surface dimensions must be the same)

INPUT DATA:  (0 = degrees, 1 = m, 2 = ft, 3 = atm, 4 = dimensionless, K or kg, 5 = psf)
Xl        x         xu        unit      res       name
22500.    26290.    30000.    1         2500.     'altitude' - altitude (if required)
1500.     1700.     2000.0    5          250.     'q0'       - dynamic pressure (if required)
.50       1.0299    1.0       4         .250      'equiv'    - equivalence ratio
1.         1.0      0.0       4         -.10      'throttle' - engine throttle (if required)
6.0       7.0       8.00      4          .5       'm0'       - Mach number
-2.00     0.0       3.00      0          .5       'AOA'      - angle of attack
5.0       4         'Mdes'      - design Mach number
0.2935    0         'AOAdes'    - design angle of attack
26000.    1         'Zdes'      - design altitude
6.2672    1         'lvehicle'  - vehicle length
5.5939    0         'thforclu'  - forebody upper surface angle
3.8700    0         'thforcll'  - forebody ramp angle
0.5873    1         'lcontrol'  - control surface length
5.0       0         'th_control'- control surface deflection angle
0.9920    0         'th_expn'   - nozzle initial expansion angle
10.8958   0         'th_exit'   - nozzle exit angle
0.0       4         'p_nozpoly' - % diff between nozzle designs [DON'T USE-defaulted to 1.]
2.901     1         'lcowl'     - cowl length (isolator/combustor)
.3        1         'lcowlext'  - cowl extension length (internal nozzle)
0.545     4         'p_iso'     - percent of lcowl that is isolator
.3238     1         'height'    - height of vehicle (if required)
20.0      1         'linlet'    - inlet length of vehicle (if required)
.28       1         'wengine'   - width of the engine (currently defaulted to unit width)
3.00      4         'iramps'    - number of inlet ramps in addition to the forebody
4.4615    0         'th_ramp1'  - inlet ramp 1 angle
5.1567    0         'th_ramp2'  - inlet ramp 2 angle
5.9844    0         'th_ramp3'  - inlet ramp 3 angle
0.0       0         'th_ramp4'  - inlet ramp 4 angle
0.0       0         'th_ramp5'  - inlet ramp 5 angle
3.09      0         'th_div1'   - first combustor expansion angle
1.2       0         'th_div2'   - second combustor expansion angle
0.01      1         'Xinjs'       - beginning of injectors (m)
0.02      1         'Xinje'     - end of injectors (m)
0.01      1         'Lmix'      - fuel mixing length (m)
1.00      4         'eta_mix'   - fuel mixing and burning efficiency
4000.     4         'Tlimit'    - maximum engine temperature (K)
90.       0         'Thetainj'  - injector angle (degrees) [90 deg. is normal to flow]
1200.     4         'Tw'        - adiabatic wall temperature (K)
0.1527    4         'nfor'      - forebody exponent n
2.0       2         'wfor'      - forebody width
2.0       1         'lfor'      - forebody length
0.2427    4         'mfor'      - forebody exponent m
5.797     0         'thforle'   - forebody leading edge angle
21.519    0         'th_le'     - leading edge attachment angle
0.0000    4         'p_kl'      - keel-line height percentage
0.25      4         'fuelfrac'  - vehicle fuel volume fraction
0.0104    2         't_plate'   - shell plate thickness (Tungsten)
0.00000   4         'mass_smb'  - mass due to Structural Modal Base (SMB) analysis
0.00000   4         'mass_tps'  - mass due to Thermal Protection System (TPS) analysis
0.00000   4         'mass_nose' - mass due to Thermal Protection System (TPS) analysis
```

Listing 9.8.2 mass_tps.DAT

```
43.06581       165.0017
```

Listing 9.8.3 masschng.dat

```
0.00000000         0.11994028E+00
0.32985264         0.27478981E+00
0.65970528         0.34499741E+00
0.98955792         0.40436554E+00
1.31941056         0.44068909E+00
1.64926314         0.45864868E+00
1.97911584         0.46505737E+00
2.30896831         0.46575165E+00
2.63882113         0.46575165E+00
2.96867371         0.46575165E+00
3.29852629         0.46575165E+00
3.62837887         0.46575165E+00
3.95823169         0.46575165E+00
4.28808403         0.46575165E+00
4.61793661         0.45078278E+00
4.94778967         0.42084122E+00
5.27764225         0.48175430E+00
5.60749483         0.63463593E+00
5.93734741         0.71089172E+00
6.26719999         0.35507202E+00
```

Listing 9.8.4 Eigenvalues and Eigenvectors of the Beam Model: RDOF_EIGEN.FREE

```
      20        20
       1     0.00000000E+00    0.00000000E+00    0.00000000E+00
       2     0.32985264E+00    0.00000000E+00    0.00000000E+00
       3     0.65970528E+00    0.00000000E+00    0.00000000E+00
       4     0.98955792E+00    0.00000000E+00    0.00000000E+00
       5     0.13194106E+01    0.00000000E+00    0.00000000E+00
       6     0.16492631E+01    0.00000000E+00    0.00000000E+00
       7     0.19791158E+01    0.00000000E+00    0.00000000E+00
       8     0.23089683E+01    0.00000000E+00    0.00000000E+00
       9     0.26388211E+01    0.00000000E+00    0.00000000E+00
      10     0.29686737E+01    0.00000000E+00    0.00000000E+00
      11     0.32985263E+01    0.00000000E+00    0.00000000E+00
      12     0.36283789E+01    0.00000000E+00    0.00000000E+00
      13     0.39582317E+01    0.00000000E+00    0.00000000E+00
      14     0.42880840E+01    0.00000000E+00    0.00000000E+00
      15     0.46179366E+01    0.00000000E+00    0.00000000E+00
      16     0.49477897E+01    0.00000000E+00    0.00000000E+00
      17     0.52776423E+01    0.00000000E+00    0.00000000E+00
      18     0.56074948E+01    0.00000000E+00    0.00000000E+00
      19     0.59373474E+01    0.00000000E+00    0.00000000E+00
      20     0.62672000E+01    0.00000000E+00    0.00000000E+00
$MODE         1
  0.24111725E-01    0.10000000E+01
      1  -0.278876328E-01   0.000000000E+00   0.112659199E-05   0.000000000E+00  -0.131874517E-05   0.000000000E+00
      2  -0.278876328E-01   0.000000000E+00   0.156158370E-05   0.000000000E+00  -0.131874616E-05   0.000000000E+00
      3  -0.278876348E-01   0.000000000E+00   0.199657550E-05   0.000000000E+00  -0.131874523E-05   0.000000000E+00
      4  -0.278876364E-01   0.000000000E+00   0.243156709E-05   0.000000000E+00  -0.131874513E-05   0.000000000E+00
      5  -0.278876407E-01   0.000000000E+00   0.286655839E-05   0.000000000E+00  -0.131874271E-05   0.000000000E+00
      6  -0.278876445E-01   0.000000000E+00   0.330154774E-05   0.000000000E+00  -0.131873266E-05   0.000000000E+00
      7  -0.278876480E-01   0.000000000E+00   0.373653169E-05   0.000000000E+00  -0.131870764E-05   0.000000000E+00
      8  -0.278876513E-01   0.000000000E+00   0.417150394E-05   0.000000000E+00  -0.131866388E-05   0.000000000E+00
      9  -0.278876515E-01   0.000000000E+00   0.460645919E-05   0.000000000E+00  -0.131860165E-05   0.000000000E+00
     10  -0.278876486E-01   0.000000000E+00   0.504139134E-05   0.000000000E+00  -0.131852787E-05   0.000000000E+00
     11  -0.278876455E-01   0.000000000E+00   0.547629834E-05   0.000000000E+00  -0.131844911E-05   0.000000000E+00
     12  -0.278876421E-01   0.000000000E+00   0.591117857E-05   0.000000000E+00  -0.131836563E-05   0.000000000E+00
     13  -0.278876385E-01   0.000000000E+00   0.634603075E-05   0.000000000E+00  -0.131827717E-05   0.000000000E+00
     14  -0.278876376E-01   0.000000000E+00   0.678085319E-05   0.000000000E+00  -0.131819208E-05   0.000000000E+00
     15  -0.278876393E-01   0.000000000E+00   0.721564925E-05   0.000000000E+00  -0.131811303E-05   0.000000000E+00
     16  -0.278876440E-01   0.000000000E+00   0.765041483E-05   0.000000000E+00  -0.131800367E-05   0.000000000E+00
     17  -0.278876521E-01   0.000000000E+00   0.808513655E-05   0.000000000E+00  -0.131785376E-05   0.000000000E+00
     18  -0.278876578E-01   0.000000000E+00   0.851982451E-05   0.000000000E+00  -0.131780157E-05   0.000000000E+00
     19  -0.278876601E-01   0.000000000E+00   0.895450277E-05   0.000000000E+00  -0.131779307E-05   0.000000000E+00
     20  -0.278876603E-01   0.000000000E+00   0.938918049E-05   0.000000000E+00  -0.131779433E-05   0.000000000E+00
$MODE         2
  0.74272821E-01    0.10000000E+01
      1  -0.590135654E-05   0.000000000E+00  -0.310373703E-01   0.000000000E+00  -0.855877568E-03   0.000000000E+00
      2  -0.590135649E-05   0.000000000E+00  -0.307550586E-01   0.000000000E+00  -0.855861192E-03   0.000000000E+00
      3  -0.590135672E-05   0.000000000E+00  -0.304727516E-01   0.000000000E+00  -0.855854660E-03   0.000000000E+00
```

```
     4  -0.590135661E-05   0.000000000E+00  -0.301904499E-01   0.000000000E+00  -0.855826006E-03   0.000000000E+00
     5  -0.590135681E-05   0.000000000E+00  -0.299081556E-01   0.000000000E+00  -0.855817760E-03   0.000000000E+00
     6  -0.590135657E-05   0.000000000E+00  -0.296258560E-01   0.000000000E+00  -0.855869346E-03   0.000000000E+00
     7  -0.590135589E-05   0.000000000E+00  -0.293435221E-01   0.000000000E+00  -0.856034073E-03   0.000000000E+00
     8  -0.590135477E-05   0.000000000E+00  -0.290611107E-01   0.000000000E+00  -0.856338226E-03   0.000000000E+00
     9  -0.590135258E-05   0.000000000E+00  -0.287785773E-01   0.000000000E+00  -0.856769639E-03   0.000000000E+00
    10  -0.590134933E-05   0.000000000E+00  -0.284958867E-01   0.000000000E+00  -0.857277176E-03   0.000000000E+00
    11  -0.590134563E-05   0.000000000E+00  -0.282130243E-01   0.000000000E+00  -0.857809629E-03   0.000000000E+00
    12  -0.590134148E-05   0.000000000E+00  -0.279299840E-01   0.000000000E+00  -0.858353217E-03   0.000000000E+00
    13  -0.590133687E-05   0.000000000E+00  -0.276467643E-01   0.000000000E+00  -0.858893951E-03   0.000000000E+00
    14  -0.590133242E-05   0.000000000E+00  -0.273633731E-01   0.000000000E+00  -0.859381798E-03   0.000000000E+00
    15  -0.590132838E-05   0.000000000E+00  -0.270798332E-01   0.000000000E+00  -0.859803354E-03   0.000000000E+00
    16  -0.590132390E-05   0.000000000E+00  -0.267961365E-01   0.000000000E+00  -0.860325023E-03   0.000000000E+00
    17  -0.590132141E-05   0.000000000E+00  -0.265122538E-01   0.000000000E+00  -0.860901326E-03   0.000000000E+00
    18  -0.590131983E-05   0.000000000E+00  -0.262282551E-01   0.000000000E+00  -0.861049662E-03   0.000000000E+00
    19  -0.590131938E-05   0.000000000E+00  -0.259442311E-01   0.000000000E+00  -0.861068348E-03   0.000000000E+00
    20  -0.590131655E-05   0.000000000E+00  -0.256602063E-01   0.000000000E+00  -0.861064754E-03   0.000000000E+00
$MODE       3
  0.11568397E+00    0.10000000E+01
     1   0.263429112E-05   0.000000000E+00  -0.576067672E-01   0.000000000E+00  -0.158799367E-01   0.000000000E+00
     2   0.263429106E-05   0.000000000E+00  -0.523687351E-01   0.000000000E+00  -0.158798715E-01   0.000000000E+00
     3   0.263429102E-05   0.000000000E+00  -0.471307271E-01   0.000000000E+00  -0.158797988E-01   0.000000000E+00
     4   0.263429067E-05   0.000000000E+00  -0.418927506E-01   0.000000000E+00  -0.158796803E-01   0.000000000E+00
     5   0.263429025E-05   0.000000000E+00  -0.366548139E-01   0.000000000E+00  -0.158795665E-01   0.000000000E+00
     6   0.263428940E-05   0.000000000E+00  -0.314169139E-01   0.000000000E+00  -0.158794752E-01   0.000000000E+00
     7   0.263428808E-05   0.000000000E+00  -0.261790343E-01   0.000000000E+00  -0.158794381E-01   0.000000000E+00
     8   0.263428628E-05   0.000000000E+00  -0.209411598E-01   0.000000000E+00  -0.158794638E-01   0.000000000E+00
     9   0.263428372E-05   0.000000000E+00  -0.157032639E-01   0.000000000E+00  -0.158795283E-01   0.000000000E+00
    10   0.263428040E-05   0.000000000E+00  -0.104653482E-01   0.000000000E+00  -0.158795970E-01   0.000000000E+00
    11   0.263427658E-05   0.000000000E+00  -0.522741415E-02   0.000000000E+00  -0.158796378E-01   0.000000000E+00
    12   0.263427228E-05   0.000000000E+00   0.105274241E-04   0.000000000E+00  -0.158796414E-01   0.000000000E+00
    13   0.263426748E-05   0.000000000E+00   0.524846637E-02   0.000000000E+00  -0.158795985E-01   0.000000000E+00
    14   0.263426246E-05   0.000000000E+00   0.104863755E-01   0.000000000E+00  -0.158795094E-01   0.000000000E+00
    15   0.263425736E-05   0.000000000E+00   0.157242531E-01   0.000000000E+00  -0.158793830E-01   0.000000000E+00
    16   0.263425218E-05   0.000000000E+00   0.209620807E-01   0.000000000E+00  -0.158791592E-01   0.000000000E+00
    17   0.263424892E-05   0.000000000E+00   0.261998071E-01   0.000000000E+00  -0.158788363E-01   0.000000000E+00
    18   0.263424675E-05   0.000000000E+00   0.314374643E-01   0.000000000E+00  -0.158787404E-01   0.000000000E+00
    19   0.263424598E-05   0.000000000E+00   0.366751062E-01   0.000000000E+00  -0.158787379E-01   0.000000000E+00
    20   0.263424238E-05   0.000000000E+00   0.419127512E-01   0.000000000E+00  -0.158787484E-01   0.000000000E+00
$MODE       4
  0.12029574E+02    0.10000000E+01
     1   0.964906826E-10   0.000000000E+00   0.840124977E-01   0.000000000E+00   0.490409242E-01   0.000000000E+00
     2   0.964664986E-10   0.000000000E+00   0.679688411E-01   0.000000000E+00   0.478347277E-01   0.000000000E+00
     3   0.963688526E-10   0.000000000E+00   0.523760494E-01   0.000000000E+00   0.463744401E-01   0.000000000E+00
     4   0.961657482E-10   0.000000000E+00   0.373023769E-01   0.000000000E+00   0.447728358E-01   0.000000000E+00
     5   0.958241807E-10   0.000000000E+00   0.228399398E-01   0.000000000E+00   0.426867590E-01   0.000000000E+00
     6   0.953227208E-10   0.000000000E+00   0.920851840E-02   0.000000000E+00   0.397296335E-01   0.000000000E+00
     7   0.946450444E-10   0.000000000E+00  -0.326712114E-02   0.000000000E+00   0.356797776E-01   0.000000000E+00
     8   0.937789716E-10   0.000000000E+00  -0.141867277E-01   0.000000000E+00   0.303044584E-01   0.000000000E+00
     9   0.927239588E-10   0.000000000E+00  -0.231207738E-01   0.000000000E+00   0.236707850E-01   0.000000000E+00
    10   0.914820785E-10   0.000000000E+00  -0.296902770E-01   0.000000000E+00   0.160166804E-01   0.000000000E+00
    11   0.900559105E-10   0.000000000E+00  -0.336118902E-01   0.000000000E+00   0.767889728E-02   0.000000000E+00
    12   0.884482921E-10   0.000000000E+00  -0.347252917E-01   0.000000000E+00  -0.938953964E-03   0.000000000E+00
    13   0.866625302E-10   0.000000000E+00  -0.330095688E-01   0.000000000E+00  -0.940116352E-02   0.000000000E+00
    14   0.847021141E-10   0.000000000E+00  -0.285879038E-01   0.000000000E+00  -0.172757883E-01   0.000000000E+00
    15   0.823218006E-10   0.000000000E+00  -0.217204306E-01   0.000000000E+00  -0.241701020E-01   0.000000000E+00
    16   0.813811565E-10   0.000000000E+00  -0.124190210E-01   0.000000000E+00  -0.318981230E-01   0.000000000E+00
    17   0.813434078E-10   0.000000000E+00  -0.453939923E-03   0.000000000E+00  -0.401316382E-01   0.000000000E+00
    18   0.812431433E-10   0.000000000E+00   0.132361151E-01   0.000000000E+00  -0.426224373E-01   0.000000000E+00
    19   0.810432696E-10   0.000000000E+00   0.274166292E-01   0.000000000E+00  -0.432463852E-01   0.000000000E+00
    20   0.790250282E-10   0.000000000E+00   0.417136351E-01   0.000000000E+00  -0.433922420E-01   0.000000000E+00
$MODE       5
  0.32143455E+02    0.10000000E+01
     1   0.199871818E-10   0.000000000E+00   0.108050990E+00   0.000000000E+00   0.108405427E+00   0.000000000E+00
     2   0.199513906E-10   0.000000000E+00   0.735110336E-01   0.000000000E+00   0.973290378E-01   0.000000000E+00
     3   0.198071414E-10   0.000000000E+00   0.429865841E-01   0.000000000E+00   0.850537745E-01   0.000000000E+00
     4   0.195083016E-10   0.000000000E+00   0.166608636E-01   0.000000000E+00   0.728529219E-01   0.000000000E+00
     5   0.190094579E-10   0.000000000E+00  -0.524957251E-02   0.000000000E+00   0.587152778E-01   0.000000000E+00
     6   0.182849603E-10   0.000000000E+00  -0.218968969E-01   0.000000000E+00   0.412631890E-01   0.000000000E+00
     7   0.173200194E-10   0.000000000E+00  -0.322629299E-01   0.000000000E+00   0.210413027E-01   0.000000000E+00
     8   0.161091952E-10   0.000000000E+00  -0.356189568E-01   0.000000000E+00  -0.745847165E-03   0.000000000E+00
     9   0.146666090E-10   0.000000000E+00  -0.319140730E-01   0.000000000E+00  -0.212307101E-01   0.000000000E+00
    10   0.130130160E-10   0.000000000E+00  -0.220941673E-01   0.000000000E+00  -0.373388713E-01   0.000000000E+00
    11   0.111721895E-10   0.000000000E+00  -0.803298100E-02   0.000000000E+00  -0.466116597E-01   0.000000000E+00
    12   0.917068790E-11   0.000000000E+00   0.775343463E-02   0.000000000E+00  -0.476775830E-01   0.000000000E+00
    13   0.703731898E-11   0.000000000E+00   0.225164239E-01   0.000000000E+00  -0.405238905E-01   0.000000000E+00
    14   0.480280220E-11   0.000000000E+00   0.337350184E-01   0.000000000E+00  -0.265286060E-01   0.000000000E+00
    15   0.283745848E-11   0.000000000E+00   0.395467900E-01   0.000000000E+00  -0.825247037E-02   0.000000000E+00
    16  -0.140902184E-11   0.000000000E+00   0.378509104E-01   0.000000000E+00   0.183662741E-01   0.000000000E+00
    17  -0.600914391E-11   0.000000000E+00   0.259102665E-01   0.000000000E+00   0.529084154E-01   0.000000000E+00
    18  -0.886789818E-11   0.000000000E+00   0.625033164E-02   0.000000000E+00   0.654067384E-01   0.000000000E+00
    19  -0.970276222E-11   0.000000000E+00  -0.160292664E-01   0.000000000E+00   0.690932937E-01   0.000000000E+00
    20  -0.934700025E-11   0.000000000E+00  -0.390341700E-01   0.000000000E+00   0.700678327E-01   0.000000000E+00
$MODE       6
  0.44486765E+02    0.10000000E+01
     1   0.415391010E-01   0.000000000E+00  -0.840198079E-10   0.000000000E+00  -0.105042882E-09   0.000000000E+00
     2   0.413966492E-01   0.000000000E+00  -0.511760075E-10   0.000000000E+00  -0.885674265E-10   0.000000000E+00
     3   0.408232078E-01   0.000000000E+00  -0.242056235E-10   0.000000000E+00  -0.712494060E-10   0.000000000E+00
     4   0.396401595E-01   0.000000000E+00  -0.303548833E-11   0.000000000E+00  -0.549449893E-10   0.000000000E+00
     5   0.376808809E-01   0.000000000E+00   0.124010427E-10   0.000000000E+00  -0.372744926E-10   0.000000000E+00
     6   0.348683388E-01   0.000000000E+00   0.215301893E-10   0.000000000E+00  -0.173138866E-10   0.000000000E+00
     7   0.311817128E-01   0.000000000E+00   0.238689120E-10   0.000000000E+00   0.322321273E-11   0.000000000E+00
     8   0.266481304E-01   0.000000000E+00   0.196247767E-10   0.000000000E+00   0.218869998E-10   0.000000000E+00
     9   0.213801924E-01   0.000000000E+00   0.100286050E-10   0.000000000E+00   0.351023792E-10   0.000000000E+00
    10   0.155230781E-01   0.000000000E+00  -0.263819065E-11   0.000000000E+00   0.402102695E-10   0.000000000E+00
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      11   0.923819160E-02   0.000000000E+00  -0.155337281E-10   0.000000000E+00   0.365610122E-10   0.000000000E+00
      12   0.269872670E-02   0.000000000E+00  -0.259694036E-10   0.000000000E+00   0.257406762E-10   0.000000000E+00
      13  -0.391511296E-02   0.000000000E+00  -0.321285313E-10   0.000000000E+00   0.114272145E-10   0.000000000E+00
      14  -0.104210534E-01   0.000000000E+00  -0.336118528E-10   0.000000000E+00  -0.191840324E-11   0.000000000E+00
      15  -0.166398250E-01   0.000000000E+00  -0.313656232E-10   0.000000000E+00  -0.106251903E-10   0.000000000E+00
      16  -0.228123536E-01   0.000000000E+00  -0.270701093E-10   0.000000000E+00  -0.139730055E-10   0.000000000E+00
      17  -0.288888705E-01   0.000000000E+00  -0.250077723E-10   0.000000000E+00   0.846500330E-11   0.000000000E+00
      18  -0.327192076E-01   0.000000000E+00  -0.312624952E-10   0.000000000E+00   0.293823538E-10   0.000000000E+00
      19  -0.346265852E-01   0.000000000E+00  -0.423241457E-10   0.000000000E+00   0.360884212E-10   0.000000000E+00
      20  -0.352638127E-01   0.000000000E+00  -0.544417511E-10   0.000000000E+00   0.370604333E-10   0.000000000E+00
$MODE         7
  0.60568742E+02    0.10000000E+01
       1  -0.157071915E-10   0.000000000E+00  -0.146473810E+00   0.000000000E+00  -0.231409075E+00   0.000000000E+00
       2  -0.156073325E-10   0.000000000E+00  -0.760049069E-01   0.000000000E+00  -0.178094660E+00   0.000000000E+00
       3  -0.152063543E-10   0.000000000E+00  -0.241108832E-01   0.000000000E+00  -0.125859035E+00   0.000000000E+00
       4  -0.143853589E-10   0.000000000E+00   0.108493324E-01   0.000000000E+00  -0.808556818E-01   0.000000000E+00
       5  -0.130450368E-10   0.000000000E+00   0.307425413E-01   0.000000000E+00  -0.372525420E-01   0.000000000E+00
       6  -0.111616129E-10   0.000000000E+00   0.360676504E-01   0.000000000E+00   0.535285715E-02   0.000000000E+00
       7  -0.876482203E-11   0.000000000E+00   0.282228388E-01   0.000000000E+00   0.406444638E-01   0.000000000E+00
       8  -0.592813575E-11   0.000000000E+00   0.108390402E-01   0.000000000E+00   0.616895581E-01   0.000000000E+00
       9  -0.278861588E-11   0.000000000E+00  -0.102565053E-01   0.000000000E+00   0.625658035E-01   0.000000000E+00
      10   0.493359032E-12   0.000000000E+00  -0.282080249E-01   0.000000000E+00   0.431790634E-01   0.000000000E+00
      11   0.375012347E-11   0.000000000E+00  -0.371976375E-01   0.000000000E+00   0.974679138E-02   0.000000000E+00
      12   0.681538703E-11   0.000000000E+00  -0.342561362E-01   0.000000000E+00  -0.271588246E-01   0.000000000E+00
      13   0.953243719E-11   0.000000000E+00  -0.201688244E-01   0.000000000E+00  -0.559879762E-01   0.000000000E+00
      14   0.117626185E-10   0.000000000E+00   0.824117689E-03   0.000000000E+00  -0.679432884E-01   0.000000000E+00
      15   0.135319732E-10   0.000000000E+00   0.224546034E-01   0.000000000E+00  -0.598979128E-01   0.000000000E+00
      16   0.137572527E-10   0.000000000E+00   0.371430507E-01   0.000000000E+00  -0.262051871E-01   0.000000000E+00
      17   0.136003648E-10   0.000000000E+00   0.351878011E-01   0.000000000E+00   0.392888226E-01   0.000000000E+00
      18   0.135923731E-10   0.000000000E+00   0.170226636E-01   0.000000000E+00   0.698021650E-01   0.000000000E+00
      19   0.144028607E-10   0.000000000E+00  -0.800874209E-02   0.000000000E+00   0.804691269E-01   0.000000000E+00
      20   0.146828531E-10   0.000000000E+00  -0.352386296E-01   0.000000000E+00   0.835929802E-01   0.000000000E+00
$MODE         8
  0.91085315E+02    0.10000000E+01
       1   0.486046744E-01   0.000000000E+00  -0.615091886E-10   0.000000000E+00  -0.137958169E-09   0.000000000E+00
       2   0.479059208E-01   0.000000000E+00  -0.215781245E-10   0.000000000E+00  -0.872069459E-10   0.000000000E+00
       3   0.451180218E-01   0.000000000E+00   0.143525607E-11   0.000000000E+00  -0.443955372E-10   0.000000000E+00
       4   0.395300384E-01   0.000000000E+00   0.114391337E-10   0.000000000E+00  -0.137377312E-10   0.000000000E+00
       5   0.307691829E-01   0.000000000E+00   0.122167219E-10   0.000000000E+00   0.906685267E-11   0.000000000E+00
       6   0.191985832E-01   0.000000000E+00   0.663164912E-11   0.000000000E+00   0.233567132E-10   0.000000000E+00
       7   0.573528155E-02   0.000000000E+00  -0.187181199E-11   0.000000000E+00   0.260902843E-10   0.000000000E+00
       8  -0.834933873E-02   0.000000000E+00  -0.927113360E-11   0.000000000E+00   0.169087703E-10   0.000000000E+00
       9  -0.214694297E-01   0.000000000E+00  -0.121693257E-10   0.000000000E+00  -0.683335989E-13   0.000000000E+00
      10  -0.321092880E-01   0.000000000E+00  -0.923090057E-11   0.000000000E+00  -0.169998573E-10   0.000000000E+00
      11  -0.390397742E-01   0.000000000E+00  -0.182214357E-11   0.000000000E+00  -0.260490252E-10   0.000000000E+00
      12  -0.414602554E-01   0.000000000E+00   0.664351032E-11   0.000000000E+00  -0.231802753E-10   0.000000000E+00
      13  -0.390911060E-01   0.000000000E+00   0.123567385E-10   0.000000000E+00  -0.101803897E-10   0.000000000E+00
      14  -0.322060325E-01   0.000000000E+00   0.129979194E-10   0.000000000E+00   0.613146646E-11   0.000000000E+00
      15  -0.216004107E-01   0.000000000E+00   0.895433644E-11   0.000000000E+00   0.165540121E-10   0.000000000E+00
      16  -0.768952060E-02   0.000000000E+00   0.291276007E-11   0.000000000E+00   0.183906918E-10   0.000000000E+00
      17   0.802661037E-02   0.000000000E+00  -0.121048707E-11   0.000000000E+00   0.306064256E-11   0.000000000E+00
      18   0.187754234E-01   0.000000000E+00  -0.269058856E-12   0.000000000E+00  -0.835920034E-11   0.000000000E+00
      19   0.245663136E-01   0.000000000E+00   0.315503354E-11   0.000000000E+00  -0.115919927E-10   0.000000000E+00
      20   0.265798168E-01   0.000000000E+00   0.706845509E-11   0.000000000E+00  -0.120002371E-10   0.000000000E+00
$MODE         9
  0.96043815E+02    0.10000000E+01
       1  -0.118311570E-10   0.000000000E+00  -0.190061228E+00   0.000000000E+00  -0.447342843E+00   0.000000000E+00
       2  -0.116420340E-10   0.000000000E+00  -0.616300092E-01   0.000000000E+00  -0.273393625E+00   0.000000000E+00
       3  -0.108885200E-10   0.000000000E+00   0.915922105E-02   0.000000000E+00  -0.129906339E+00   0.000000000E+00
       4  -0.938467036E-11   0.000000000E+00   0.368905308E-01   0.000000000E+00  -0.307390709E-01   0.000000000E+00
       5  -0.704655292E-11   0.000000000E+00   0.353776408E-01   0.000000000E+00   0.391381597E-01   0.000000000E+00
       6  -0.399883833E-11   0.000000000E+00   0.152167735E-01   0.000000000E+00   0.777120202E-01   0.000000000E+00
       7  -0.521845317E-12   0.000000000E+00  -0.114945238E-01   0.000000000E+00   0.772803593E-01   0.000000000E+00
       8   0.301168410E-11   0.000000000E+00  -0.317458597E-01   0.000000000E+00   0.401741901E-01   0.000000000E+00
       9   0.615838813E-11   0.000000000E+00  -0.358962654E-01   0.000000000E+00  -0.160438435E-01   0.000000000E+00
      10   0.851408638E-11   0.000000000E+00  -0.220831031E-01   0.000000000E+00  -0.638813728E-01   0.000000000E+00
      11   0.977620973E-11   0.000000000E+00   0.273416931E-02   0.000000000E+00  -0.797734440E-01   0.000000000E+00
      12   0.978262706E-11   0.000000000E+00   0.261667458E-01   0.000000000E+00  -0.558559467E-01   0.000000000E+00
      13   0.853267431E-11   0.000000000E+00   0.364970483E-01   0.000000000E+00  -0.387521114E-02   0.000000000E+00
      14   0.618673905E-11   0.000000000E+00   0.284380250E-01   0.000000000E+00   0.506997352E-01   0.000000000E+00
      15   0.307666506E-11   0.000000000E+00   0.566675410E-02   0.000000000E+00   0.814770172E-01   0.000000000E+00
      16  -0.125624964E-11   0.000000000E+00  -0.211700735E-01   0.000000000E+00   0.720839937E-01   0.000000000E+00
      17  -0.598732336E-11   0.000000000E+00  -0.331797150E-01   0.000000000E+00  -0.817119032E-02   0.000000000E+00
      18  -0.948187330E-11   0.000000000E+00  -0.217586392E-01   0.000000000E+00  -0.615052754E-01   0.000000000E+00
      19  -0.125202160E-10   0.000000000E+00   0.262655711E-02   0.000000000E+00  -0.836303031E-01   0.000000000E+00
      20  -0.133506200E-10   0.000000000E+00   0.317694569E-01   0.000000000E+00  -0.907118081E-01   0.000000000E+00
$MODE        10
  0.13745102E+03    0.10000000E+01
       1  -0.246574144E-10   0.000000000E+00  -0.211240645E+00   0.000000000E+00  -0.703891609E+00   0.000000000E+00
       2  -0.238501994E-10   0.000000000E+00  -0.225982289E-01   0.000000000E+00  -0.307917874E+00   0.000000000E+00
       3  -0.206778819E-10   0.000000000E+00   0.423576344E-01   0.000000000E+00  -0.497547363E-01   0.000000000E+00
       4  -0.146320296E-10   0.000000000E+00   0.383106762E-01   0.000000000E+00   0.727769033E-01   0.000000000E+00
       5  -0.606183786E-11   0.000000000E+00   0.671915168E-02   0.000000000E+00   0.106761986E+00   0.000000000E+00
       6   0.351785649E-11   0.000000000E+00  -0.244010324E-01   0.000000000E+00   0.703426600E-01   0.000000000E+00
       7   0.119535875E-10   0.000000000E+00  -0.355937659E-01   0.000000000E+00  -0.636596109E-02   0.000000000E+00
       8   0.172242595E-10   0.000000000E+00  -0.210619130E-01   0.000000000E+00  -0.757297929E-01   0.000000000E+00
       9   0.179637550E-10   0.000000000E+00   0.846936050E-02   0.000000000E+00  -0.914677846E-01   0.000000000E+00
      10   0.139775500E-10   0.000000000E+00   0.322310864E-01   0.000000000E+00  -0.430974136E-01   0.000000000E+00
      11   0.631432870E-11   0.000000000E+00   0.335773669E-01   0.000000000E+00   0.355007295E-01   0.000000000E+00
      12  -0.301004722E-11   0.000000000E+00   0.115107659E-01   0.000000000E+00   0.895453077E-01   0.000000000E+00
      13  -0.115425690E-10   0.000000000E+00  -0.186696566E-01   0.000000000E+00   0.815032575E-01   0.000000000E+00
      14  -0.170385168E-10   0.000000000E+00  -0.360861060E-01   0.000000000E+00   0.173339658E-01   0.000000000E+00
      15  -0.180790047E-10   0.000000000E+00  -0.289453280E-01   0.000000000E+00  -0.573819796E-01   0.000000000E+00
      16  -0.124411695E-10   0.000000000E+00  -0.238405268E-03   0.000000000E+00  -0.101478865E+00   0.000000000E+00
      17  -0.317168047E-11   0.000000000E+00   0.255630130E-01   0.000000000E+00  -0.327928255E-01   0.000000000E+00
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     18   0.470419848E-11   0.000000000E+00   0.240043415E-01   0.000000000E+00   0.468674461E-01   0.000000000E+00
     19   0.113506740E-10   0.000000000E+00   0.134899950E-02   0.000000000E+00   0.863832671E-01   0.000000000E+00
     20   0.134787415E-10   0.000000000E+00  -0.301739843E-01   0.000000000E+00   0.100158763E+00   0.000000000E+00
$MODE       11
  0.14015957E+03    0.10000000E+01
      1  -0.576291542E-01   0.000000000E+00   0.980725269E-10   0.000000000E+00   0.333242682E-09   0.000000000E+00
      2  -0.556674342E-01   0.000000000E+00   0.915710684E-11   0.000000000E+00   0.142236436E-09   0.000000000E+00
      3  -0.479663635E-01   0.000000000E+00  -0.203000887E-10   0.000000000E+00   0.196413091E-10   0.000000000E+00
      4  -0.333434330E-01   0.000000000E+00  -0.172936900E-10   0.000000000E+00  -0.366727253E-10   0.000000000E+00
      5  -0.127725064E-01   0.000000000E+00  -0.199744418E-11   0.000000000E+00  -0.501725289E-10   0.000000000E+00
      6   0.991298862E-02   0.000000000E+00   0.121848098E-10   0.000000000E+00  -0.304458686E-10   0.000000000E+00
      7   0.293789839E-01   0.000000000E+00   0.163587104E-10   0.000000000E+00   0.659049826E-11   0.000000000E+00
      8   0.407627449E-01   0.000000000E+00   0.851681997E-11   0.000000000E+00   0.376644694E-10   0.000000000E+00
      9   0.409963232E-01   0.000000000E+00  -0.550707781E-11   0.000000000E+00   0.416219107E-10   0.000000000E+00
     10   0.300158201E-01   0.000000000E+00  -0.156767713E-10   0.000000000E+00   0.158738949E-10   0.000000000E+00
     11   0.108248340E-01   0.000000000E+00  -0.147259636E-10   0.000000000E+00  -0.212766396E-10   0.000000000E+00
     12  -0.113271610E-01   0.000000000E+00  -0.328217995E-11   0.000000000E+00  -0.435006629E-10   0.000000000E+00
     13  -0.303807559E-01   0.000000000E+00   0.106165107E-10   0.000000000E+00  -0.352212832E-10   0.000000000E+00
     14  -0.411240236E-01   0.000000000E+00   0.173048815E-10   0.000000000E+00  -0.286157598E-11   0.000000000E+00
     15  -0.406183041E-01   0.000000000E+00   0.126151584E-10   0.000000000E+00   0.284597181E-10   0.000000000E+00
     16  -0.286052067E-01   0.000000000E+00   0.648870766E-13   0.000000000E+00   0.414527431E-10   0.000000000E+00
     17  -0.884350721E-02   0.000000000E+00  -0.977004608E-11   0.000000000E+00   0.105932084E-10   0.000000000E+00
     18   0.733984027E-02   0.000000000E+00  -0.876257858E-11   0.000000000E+00  -0.173007938E-10   0.000000000E+00
     19   0.175849757E-01   0.000000000E+00  -0.817496843E-12   0.000000000E+00  -0.294238969E-10   0.000000000E+00
     20   0.214286212E-01   0.000000000E+00   0.975524492E-11   0.000000000E+00  -0.333674641E-10   0.000000000E+00
$MODE       12
  0.18549657E+03    0.10000000E+01
      1  -0.404638507E-10   0.000000000E+00  -0.201509387E+00   0.000000000E+00  -0.919062790E+00   0.000000000E+00
      2  -0.380511930E-10   0.000000000E+00   0.260030227E-01   0.000000000E+00  -0.231102444E+00   0.000000000E+00
      3  -0.287813835E-10   0.000000000E+00   0.528310696E-01   0.000000000E+00   0.882162354E-01   0.000000000E+00
      4  -0.124550558E-10   0.000000000E+00   0.103583327E-01   0.000000000E+00   0.144242441E+00   0.000000000E+00
      5   0.700349952E-11   0.000000000E+00  -0.286319824E-01   0.000000000E+00   0.718209970E-01   0.000000000E+00
      6   0.223093093E-10   0.000000000E+00  -0.337885403E-01   0.000000000E+00  -0.426620603E-01   0.000000000E+00
      7   0.267462480E-10   0.000000000E+00  -0.644849833E-02   0.000000000E+00  -0.108138426E+00   0.000000000E+00
      8   0.183747313E-10   0.000000000E+00   0.266180697E-01   0.000000000E+00  -0.742932677E-01   0.000000000E+00
      9   0.119949323E-11   0.000000000E+00   0.350849221E-01   0.000000000E+00   0.275657554E-01   0.000000000E+00
     10  -0.165504652E-10   0.000000000E+00   0.112403409E-01   0.000000000E+00   0.103890459E+00   0.000000000E+00
     11  -0.263707108E-10   0.000000000E+00  -0.229223128E-01   0.000000000E+00   0.844470314E-01   0.000000000E+00
     12  -0.235562509E-10   0.000000000E+00  -0.358873191E-01   0.000000000E+00  -0.130534743E-01   0.000000000E+00
     13  -0.945550873E-11   0.000000000E+00  -0.155317805E-01   0.000000000E+00  -0.994497062E-01   0.000000000E+00
     14   0.917557331E-11   0.000000000E+00   0.199277637E-01   0.000000000E+00  -0.967849148E-01   0.000000000E+00
     15   0.232854759E-10   0.000000000E+00   0.392581119E-01   0.000000000E+00  -0.117238642E-01   0.000000000E+00
     16   0.243752766E-10   0.000000000E+00   0.225861810E-01   0.000000000E+00   0.983544682E-01   0.000000000E+00
     17   0.145431683E-10   0.000000000E+00  -0.131395540E-01   0.000000000E+00   0.797819963E-01   0.000000000E+00
     18   0.187924312E-11   0.000000000E+00  -0.244277528E-01   0.000000000E+00  -0.242919674E-01   0.000000000E+00
     19  -0.113623925E-10   0.000000000E+00  -0.505771197E-02   0.000000000E+00  -0.879574032E-01   0.000000000E+00
     20  -0.164037194E-10   0.000000000E+00   0.293153727E-01   0.000000000E+00  -0.112332562E+00   0.000000000E+00
$MODE       13
  0.18866591E+03    0.10000000E+01
      1   0.635456904E-01   0.000000000E+00  -0.128079834E-09   0.000000000E+00  -0.595027517E-09   0.000000000E+00
      2   0.596262662E-01   0.000000000E+00   0.184466311E-10   0.000000000E+00  -0.142630666E-09   0.000000000E+00
      3   0.445932641E-01   0.000000000E+00   0.336042251E-10   0.000000000E+00   0.619395460E-10   0.000000000E+00
      4   0.182827976E-01   0.000000000E+00   0.520964192E-11   0.000000000E+00   0.931262188E-10   0.000000000E+00
      5  -0.126132500E-01   0.000000000E+00  -0.192533068E-10   0.000000000E+00   0.421772862E-10   0.000000000E+00
      6  -0.360622671E-01   0.000000000E+00  -0.209869909E-10   0.000000000E+00  -0.322093635E-10   0.000000000E+00
      7  -0.413893820E-01   0.000000000E+00  -0.232926801E-11   0.000000000E+00  -0.705454456E-10   0.000000000E+00
      8  -0.262178436E-01   0.000000000E+00   0.183234681E-10   0.000000000E+00  -0.432087710E-10   0.000000000E+00
      9   0.194814539E-02   0.000000000E+00   0.217658578E-10   0.000000000E+00   0.242314316E-10   0.000000000E+00
     10   0.291485491E-01   0.000000000E+00   0.483710339E-11   0.000000000E+00   0.689086061E-10   0.000000000E+00
     11   0.419019812E-01   0.000000000E+00  -0.165994622E-10   0.000000000E+00   0.490460267E-10   0.000000000E+00
     12   0.338874248E-01   0.000000000E+00  -0.224529192E-10   0.000000000E+00  -0.168914751E-10   0.000000000E+00
     13   0.907712925E-02   0.000000000E+00  -0.712224271E-11   0.000000000E+00  -0.676667245E-10   0.000000000E+00
     14  -0.202320451E-01   0.000000000E+00   0.154316753E-10   0.000000000E+00  -0.570045845E-10   0.000000000E+00
     15  -0.395135858E-01   0.000000000E+00   0.252629817E-10   0.000000000E+00   0.111229779E-11   0.000000000E+00
     16  -0.398975614E-01   0.000000000E+00   0.125320985E-10   0.000000000E+00   0.657282754E-10   0.000000000E+00
     17  -0.229669845E-01   0.000000000E+00  -0.964425189E-11   0.000000000E+00   0.458824898E-10   0.000000000E+00
     18  -0.217392360E-02   0.000000000E+00  -0.155140169E-10   0.000000000E+00  -0.168695751E-10   0.000000000E+00
     19   0.154271620E-01   0.000000000E+00  -0.339842644E-11   0.000000000E+00  -0.535861511E-10   0.000000000E+00
     20   0.228552354E-01   0.000000000E+00   0.173654672E-10   0.000000000E+00  -0.676305216E-10   0.000000000E+00
$MODE       14
  0.23272215E+03    0.10000000E+01
      1   0.629441732E-01   0.000000000E+00   0.381452117E-10   0.000000000E+00   0.223647642E-09   0.000000000E+00
      2   0.570369925E-01   0.000000000E+00  -0.130972860E-10   0.000000000E+00   0.187294540E-10   0.000000000E+00
      3   0.349998252E-01   0.000000000E+00  -0.840209429E-11   0.000000000E+00  -0.414391601E-10   0.000000000E+00
      4   0.253051461E-03   0.000000000E+00   0.441981227E-11   0.000000000E+00  -0.263159255E-10   0.000000000E+00
      5  -0.307485051E-01   0.000000000E+00   0.794513811E-11   0.000000000E+00   0.721423131E-11   0.000000000E+00
      6  -0.386506051E-01   0.000000000E+00   0.166087382E-11   0.000000000E+00   0.264532754E-10   0.000000000E+00
      7  -0.177459453E-01   0.000000000E+00  -0.617960661E-11   0.000000000E+00   0.157279450E-10   0.000000000E+00
      8   0.164587127E-01   0.000000000E+00  -0.683988368E-11   0.000000000E+00  -0.121296363E-10   0.000000000E+00
      9   0.382513236E-01   0.000000000E+00   0.290908844E-12   0.000000000E+00  -0.260831878E-10   0.000000000E+00
     10   0.311972872E-01   0.000000000E+00   0.712371065E-11   0.000000000E+00  -0.105282004E-10   0.000000000E+00
     11   0.616320528E-03   0.000000000E+00   0.592138413E-11   0.000000000E+00   0.169641350E-10   0.000000000E+00
     12  -0.304294343E-01   0.000000000E+00  -0.194812553E-11   0.000000000E+00   0.251872584E-10   0.000000000E+00
     13  -0.385273216E-01   0.000000000E+00  -0.753954195E-11   0.000000000E+00   0.469814659E-11   0.000000000E+00
     14  -0.175704640E-01   0.000000000E+00  -0.440525282E-11   0.000000000E+00  -0.216322321E-10   0.000000000E+00
     15   0.166368826E-01   0.000000000E+00   0.420566895E-11   0.000000000E+00  -0.249305757E-10   0.000000000E+00
     16   0.402391557E-01   0.000000000E+00   0.849457361E-11   0.000000000E+00   0.152034946E-11   0.000000000E+00
     17   0.389683581E-01   0.000000000E+00   0.264264466E-11   0.000000000E+00   0.252984815E-10   0.000000000E+00
     18   0.161759943E-01   0.000000000E+00  -0.340773330E-11   0.000000000E+00   0.496645049E-11   0.000000000E+00
     19  -0.164870406E-01   0.000000000E+00  -0.179292871E-11   0.000000000E+00  -0.136446403E-10   0.000000000E+00
     20  -0.326162494E-01   0.000000000E+00   0.441064323E-11   0.000000000E+00  -0.213883944E-10   0.000000000E+00
$MODE       15
  0.24109437E+03    0.10000000E+01
      1  -0.128965633E-10   0.000000000E+00   0.174376328E+00   0.000000000E+00   0.106464443E+01   0.000000000E+00
      2  -0.115975736E-10   0.000000000E+00  -0.662214216E-01   0.000000000E+00   0.589590428E-01   0.000000000E+00
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   3  -0.678081910E-11   0.000000000E+00  -0.355138989E-01   0.000000000E+00  -0.207183277E+00   0.000000000E+00
   4   0.635080091E-12   0.000000000E+00   0.252304352E-01   0.000000000E+00  -0.111722142E+00   0.000000000E+00
   5   0.678992500E-11   0.000000000E+00   0.359866380E-01   0.000000000E+00   0.533108757E-01   0.000000000E+00
   6   0.753484821E-11   0.000000000E+00   0.186750973E-02   0.000000000E+00   0.128542777E+00   0.000000000E+00
   7   0.227497559E-11   0.000000000E+00  -0.324954528E-01   0.000000000E+00   0.553688494E-01   0.000000000E+00
   8  -0.480771752E-11   0.000000000E+00  -0.280230460E-01   0.000000000E+00  -0.789625936E-01   0.000000000E+00
   9  -0.799913295E-11   0.000000000E+00   0.938053712E-02   0.000000000E+00  -0.120379743E+00   0.000000000E+00
  10  -0.471632615E-11   0.000000000E+00   0.359262969E-01   0.000000000E+00  -0.211365652E-01   0.000000000E+00
  11   0.238378008E-11   0.000000000E+00   0.206170566E-01   0.000000000E+00   0.102730016E+00   0.000000000E+00
  12   0.755457792E-11   0.000000000E+00  -0.186299703E-01   0.000000000E+00   0.106404988E+00   0.000000000E+00
  13   0.661101344E-11   0.000000000E+00  -0.358040402E-01   0.000000000E+00  -0.152009527E-01   0.000000000E+00
  14   0.316764311E-12   0.000000000E+00  -0.101557245E-01   0.000000000E+00  -0.122674731E+00   0.000000000E+00
  15  -0.652850854E-11   0.000000000E+00   0.306289516E-01   0.000000000E+00  -0.983074011E-01   0.000000000E+00
  16  -0.104800683E-10   0.000000000E+00   0.390623823E-01   0.000000000E+00   0.486143128E-01   0.000000000E+00
  17  -0.862821076E-11   0.000000000E+00   0.296745791E-02   0.000000000E+00   0.121241840E+00   0.000000000E+00
  18  -0.218104947E-11   0.000000000E+00  -0.224647857E-01   0.000000000E+00   0.691695211E-02   0.000000000E+00
  19   0.276990111E-11   0.000000000E+00  -0.872605313E-02   0.000000000E+00  -0.854280070E-01   0.000000000E+00
  20   0.597666417E-11   0.000000000E+00   0.281462488E-01   0.000000000E+00  -0.124962539E+00   0.000000000E+00
$MODE       16
 0.26795948E+03    0.10000000E+01
   1   0.602908611E-01   0.000000000E+00   0.730095316E-11   0.000000000E+00   0.504949754E-10   0.000000000E+00
   2   0.527895178E-01   0.000000000E+00  -0.360892840E-11   0.000000000E+00  -0.170562411E-11   0.000000000E+00
   3   0.255533062E-01   0.000000000E+00  -0.977328933E-12   0.000000000E+00  -0.107301965E-10   0.000000000E+00
   4  -0.128886269E-01   0.000000000E+00   0.166468632E-11   0.000000000E+00  -0.284279312E-11   0.000000000E+00
   5  -0.362865813E-01   0.000000000E+00   0.124893102E-11   0.000000000E+00   0.499090766E-11   0.000000000E+00
   6  -0.249030456E-01   0.000000000E+00  -0.744430537E-12   0.000000000E+00   0.546657819E-11   0.000000000E+00
   7   0.106413916E-01   0.000000000E+00  -0.165049698E-11   0.000000000E+00  -0.691230242E-12   0.000000000E+00
   8   0.354565709E-01   0.000000000E+00  -0.406355382E-12   0.000000000E+00  -0.581057073E-11   0.000000000E+00
   9   0.248224140E-01   0.000000000E+00   0.135938201E-11   0.000000000E+00  -0.343523969E-11   0.000000000E+00
  10  -0.106290889E-01   0.000000000E+00   0.137350332E-11   0.000000000E+00   0.335336909E-11   0.000000000E+00
  11  -0.354536745E-01   0.000000000E+00  -0.379501097E-12   0.000000000E+00   0.583453557E-11   0.000000000E+00
  12  -0.248318288E-01   0.000000000E+00  -0.166070661E-11   0.000000000E+00   0.899303906E-12   0.000000000E+00
  13   0.106168102E-01   0.000000000E+00  -0.862482353E-12   0.000000000E+00  -0.501725591E-11   0.000000000E+00
  14   0.354507620E-01   0.000000000E+00   0.946757565E-12   0.000000000E+00  -0.455557497E-11   0.000000000E+00
  15   0.248412319E-01   0.000000000E+00   0.144090469E-11   0.000000000E+00   0.225205972E-11   0.000000000E+00
  16  -0.121424675E-01   0.000000000E+00  -0.549016461E-12   0.000000000E+00   0.743323508E-11   0.000000000E+00
  17  -0.412071811E-01   0.000000000E+00  -0.181389226E-11   0.000000000E+00  -0.190286052E-11   0.000000000E+00
  18  -0.317051694E-01   0.000000000E+00  -0.489581826E-12   0.000000000E+00  -0.440140522E-11   0.000000000E+00
  19   0.142055207E-01   0.000000000E+00   0.793317129E-12   0.000000000E+00  -0.359385194E-11   0.000000000E+00
  20   0.412476863E-01   0.000000000E+00   0.196193732E-11   0.000000000E+00  -0.351739795E-11   0.000000000E+00
$MODE       17
 0.30274189E+03    0.10000000E+01
   1   0.678914109E-01   0.000000000E+00  -0.242836547E-10   0.000000000E+00  -0.193735907E-09   0.000000000E+00
   2   0.571091667E-01   0.000000000E+00   0.153328053E-10   0.000000000E+00   0.271708447E-10   0.000000000E+00
   3   0.191703626E-01   0.000000000E+00   0.219952386E-12   0.000000000E+00   0.414001045E-10   0.000000000E+00
   4  -0.272981552E-01   0.000000000E+00  -0.753557041E-11   0.000000000E+00  -0.269515625E-11   0.000000000E+00
   5  -0.395507567E-01   0.000000000E+00  -0.175638377E-11   0.000000000E+00  -0.266985746E-10   0.000000000E+00
   6  -0.451088286E-02   0.000000000E+00   0.568658078E-11   0.000000000E+00  -0.114895782E-10   0.000000000E+00
   7   0.353186265E-01   0.000000000E+00   0.445836376E-11   0.000000000E+00   0.177196561E-10   0.000000000E+00
   8   0.300240927E-01   0.000000000E+00  -0.317578892E-11   0.000000000E+00   0.213470800E-10   0.000000000E+00
   9  -0.135871719E-01   0.000000000E+00  -0.628072161E-11   0.000000000E+00  -0.545993891E-11   0.000000000E+00
  10  -0.398584769E-01   0.000000000E+00  -0.427459359E-12   0.000000000E+00  -0.245057174E-10   0.000000000E+00
  11  -0.152624755E-01   0.000000000E+00   0.604546871E-11   0.000000000E+00  -0.864209259E-11   0.000000000E+00
  12   0.288114658E-01   0.000000000E+00   0.393373653E-11   0.000000000E+00   0.194185528E-10   0.000000000E+00
  13   0.361162672E-01   0.000000000E+00  -0.367574057E-11   0.000000000E+00   0.193849955E-10   0.000000000E+00
  14  -0.267041190E-02   0.000000000E+00  -0.575036263E-11   0.000000000E+00  -0.884793895E-11   0.000000000E+00
  15  -0.380491465E-01   0.000000000E+00   0.108629456E-11   0.000000000E+00  -0.272628822E-10   0.000000000E+00
  16  -0.257182729E-01   0.000000000E+00   0.835145739E-11   0.000000000E+00  -0.981592811E-11   0.000000000E+00
  17   0.163077765E-01   0.000000000E+00   0.431622863E-11   0.000000000E+00   0.284897279E-10   0.000000000E+00
  18   0.314095494E-01   0.000000000E+00  -0.369399397E-11   0.000000000E+00   0.107854254E-10   0.000000000E+00
  19  -0.539753052E-02   0.000000000E+00  -0.324926132E-11   0.000000000E+00  -0.129681227E-10   0.000000000E+00
  20  -0.330836428E-01   0.000000000E+00   0.350574488E-11   0.000000000E+00  -0.242343211E-10   0.000000000E+00
$MODE       18
 0.30414468E+03    0.10000000E+01
   1  -0.114110200E-10   0.000000000E+00  -0.136579397E+00   0.000000000E+00  -0.109550701E+01   0.000000000E+00
   2  -0.958194820E-11   0.000000000E+00   0.869411842E-01   0.000000000E+00   0.158070589E+00   0.000000000E+00
   3  -0.315484076E-11   0.000000000E+00   0.449925024E-03   0.000000000E+00   0.233643471E+00   0.000000000E+00
   4   0.466571232E-11   0.000000000E+00  -0.427691843E-01   0.000000000E+00  -0.183148292E-01   0.000000000E+00
   5   0.660582078E-11   0.000000000E+00  -0.923623327E-02   0.000000000E+00  -0.151999977E+00   0.000000000E+00
   6   0.580500229E-12   0.000000000E+00   0.325968338E-01   0.000000000E+00  -0.624248959E-01   0.000000000E+00
   7  -0.603067412E-11   0.000000000E+00   0.245868805E-01   0.000000000E+00   0.103011886E+00   0.000000000E+00
   8  -0.486608707E-11   0.000000000E+00  -0.188686097E-01   0.000000000E+00   0.119226742E+00   0.000000000E+00
   9   0.256628217E-11   0.000000000E+00  -0.353127679E-01   0.000000000E+00  -0.351316561E-01   0.000000000E+00
  10   0.669312808E-11   0.000000000E+00  -0.121861749E-02   0.000000000E+00  -0.139226880E+00   0.000000000E+00
  11   0.219889376E-11   0.000000000E+00   0.346378867E-01   0.000000000E+00  -0.441617480E-01   0.000000000E+00
  12  -0.512764206E-11   0.000000000E+00   0.209938906E-01   0.000000000E+00   0.113851201E+00   0.000000000E+00
  13  -0.584957288E-11   0.000000000E+00  -0.224602545E-01   0.000000000E+00   0.108064005E+00   0.000000000E+00
  14   0.963119406E-12   0.000000000E+00  -0.329435777E-01   0.000000000E+00  -0.555464437E-01   0.000000000E+00
  15   0.619306086E-11   0.000000000E+00   0.670781103E-02   0.000000000E+00  -0.151161485E+00   0.000000000E+00
  16   0.270256080E-11   0.000000000E+00   0.439705572E-01   0.000000000E+00  -0.403912630E-01   0.000000000E+00
  17  -0.594964533E-11   0.000000000E+00   0.197833091E-01   0.000000000E+00   0.145448225E+00   0.000000000E+00
  18  -0.637834283E-11   0.000000000E+00  -0.187101250E-01   0.000000000E+00   0.443490736E-01   0.000000000E+00
  19   0.132146968E-11   0.000000000E+00  -0.125650402E-01   0.000000000E+00  -0.802927503E-01   0.000000000E+00
  20   0.814970105E-11   0.000000000E+00   0.273769109E-01   0.000000000E+00  -0.141489568E+00   0.000000000E+00
$MODE       19
 0.34073782E+03    0.10000000E+01
   1  -0.707538826E-01   0.000000000E+00   0.286928532E-12   0.000000000E+00   0.262347720E-11   0.000000000E+00
   2  -0.565194476E-01   0.000000000E+00  -0.221984002E-12   0.000000000E+00  -0.690287092E-12   0.000000000E+00
   3  -0.840091489E-02   0.000000000E+00   0.480007977E-13   0.000000000E+00  -0.495289349E-12   0.000000000E+00
   4   0.394299547E-01   0.000000000E+00   0.105439962E-12   0.000000000E+00   0.235797171E-12   0.000000000E+00
   5   0.288337445E-01   0.000000000E+00  -0.219086549E-13   0.000000000E+00   0.399183609E-12   0.000000000E+00
   6  -0.242519715E-01   0.000000000E+00  -0.938925746E-13   0.000000000E+00  -0.298463827E-13   0.000000000E+00
   7  -0.375458217E-01   0.000000000E+00  -0.115502451E-13   0.000000000E+00  -0.367137329E-12   0.000000000E+00
   8   0.980588267E-02   0.000000000E+00   0.869057320E-13   0.000000000E+00  -0.124434647E-12   0.000000000E+00
   9   0.413050297E-01   0.000000000E+00   0.469408709E-13   0.000000000E+00   0.322686439E-12   0.000000000E+00
```

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      10   0.602871042E-02   0.000000000E+00  -0.675104098E-13   0.000000000E+00   0.247050254E-12   0.000000000E+00
      11  -0.389938711E-01   0.000000000E+00  -0.712141591E-13   0.000000000E+00  -0.237902197E-12   0.000000000E+00
      12  -0.209773503E-01   0.000000000E+00   0.541938680E-13   0.000000000E+00  -0.403252596E-12   0.000000000E+00
      13   0.309520756E-01   0.000000000E+00   0.149909210E-12   0.000000000E+00  -0.172574001E-12   0.000000000E+00
      14   0.328430569E-01   0.000000000E+00   0.122588716E-12   0.000000000E+00   0.472429997E-12   0.000000000E+00
      15  -0.183613752E-01   0.000000000E+00  -0.103128223E-12   0.000000000E+00   0.583827601E-12   0.000000000E+00
      16  -0.424328354E-01   0.000000000E+00  -0.503939203E-13   0.000000000E+00  -0.107313464E-11   0.000000000E+00
      17  -0.811679272E-02   0.000000000E+00   0.242277663E-12   0.000000000E+00   0.105857230E-11   0.000000000E+00
      18   0.266238962E-01   0.000000000E+00  -0.370053959E-12   0.000000000E+00   0.164557042E-11   0.000000000E+00
      19   0.161849488E-02   0.000000000E+00  -0.771139226E-12   0.000000000E+00   0.103414361E-11   0.000000000E+00
      20  -0.269328262E-01   0.000000000E+00  -0.112669386E-11   0.000000000E+00   0.109978557E-11   0.000000000E+00
$MODE        20
  0.37463267E+03    0.10000000E+01
       1  -0.355947090E-11   0.000000000E+00   0.958891159E-01   0.000000000E+00   0.995287908E+00   0.000000000E+00
       2  -0.269382803E-11   0.000000000E+00  -0.855826082E-01   0.000000000E+00  -0.340053935E+00   0.000000000E+00
       3   0.113863383E-12   0.000000000E+00   0.332714032E-01   0.000000000E+00  -0.148576036E+00   0.000000000E+00
       4   0.225867224E-11   0.000000000E+00   0.320750366E-01   0.000000000E+00   0.154238522E+00   0.000000000E+00
       5   0.488809278E-12   0.000000000E+00  -0.248642677E-01   0.000000000E+00   0.120952523E+00   0.000000000E+00
       6  -0.206780838E-11   0.000000000E+00  -0.303011707E-01   0.000000000E+00  -0.938110068E-01   0.000000000E+00
       7  -0.594716624E-12   0.000000000E+00   0.170112184E-01   0.000000000E+00  -0.136577282E+00   0.000000000E+00
       8   0.203444028E-11   0.000000000E+00   0.345172400E-01   0.000000000E+00   0.512864949E-01   0.000000000E+00
       9   0.687752556E-12   0.000000000E+00  -0.711062651E-02   0.000000000E+00   0.150819297E+00   0.000000000E+00
      10  -0.200299372E-11   0.000000000E+00  -0.366317617E-01   0.000000000E+00  -0.746299547E-02   0.000000000E+00
      11  -0.779376076E-12   0.000000000E+00  -0.358257357E-02   0.000000000E+00  -0.153054996E+00   0.000000000E+00
      12   0.196727405E-11   0.000000000E+00   0.356003830E-01   0.000000000E+00  -0.372691834E-01   0.000000000E+00
      13   0.869093832E-12   0.000000000E+00   0.140355313E-01   0.000000000E+00   0.141894644E+00   0.000000000E+00
      14  -0.192748717E-11   0.000000000E+00  -0.312268376E-01   0.000000000E+00   0.774851990E-01   0.000000000E+00
      15  -0.116408916E-11   0.000000000E+00  -0.219896528E-01   0.000000000E+00  -0.124185553E+00   0.000000000E+00
      16   0.272999754E-11   0.000000000E+00   0.343504652E-01   0.000000000E+00  -0.144112587E+00   0.000000000E+00
      17   0.341732276E-12   0.000000000E+00   0.346565590E-01   0.000000000E+00   0.140226171E+00   0.000000000E+00
      18  -0.142483334E-11   0.000000000E+00  -0.131227186E-01   0.000000000E+00   0.864021047E-01   0.000000000E+00
      19  -0.653929602E-12   0.000000000E+00  -0.168075647E-01   0.000000000E+00  -0.719059785E-01   0.000000000E+00
      20   0.323921072E-11   0.000000000E+00   0.271864737E-01   0.000000000E+00  -0.164110128E+00   0.000000000E+00
```

Listing 9.8.5 trim_output.dat

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          ------------------------------------------------------

          TRIM ITERATION NUMBER :    1

          SUMMARY  OF  TOTAL  AERODYNAMIC   FORCES  AND  MOMENTS

          MEAN FLOW CONDITION :

          MACH NUMBER                          : 0.700000E+01
          ALTITUDE IN METERS                   : 0.254684E+05
          DYNAMIC PRESSURE IN N/M^2            : 0.813965E+05
          ANGLE OF ATTACK IN DEGREES           : 0.000000E+00
          CONTROL SURFACE DEFLECTION IN DEGREES : 0.500000E+01

          TRIM VARIABLE: ALPHA = 0.187930E+00(DEG), DELTA = 0.159617E+03(DEG)

          FINAL TRIM POSITION: ALPHA = 0.187930E+00(DEG), DELTA = 0.164617E+03(DEG)

          ------------------------------------------------------
           AERODYNAMIC STABILITY DERIVATIVES OF FULL SPAN MODEL
           REFERENCE AREA =     1.829348      REFERENCE CHORD =      6.267200
           X-CG =     3.369830       Z-CG =    6.4264284E-03
           TOTAL WEIGHT =     6515.901      NEWTON
           X AERODYNAMIC CENTER FROM X = 0 :     7.569181

                          DRAG COEFFICIENT                LIFT COEFFICIENT                MOMENT COEFFICIENT

                          RIGID           ELASTIC         RIGID           ELASTIC         RIGID           ELASTIC

MEAN FLOW                 0.5378E-01      0.5216E-01      0.8156E-01      0.8187E-01      -.2366E-01      -.2383E-01

ALPHA(/RAD)               0.1395E+01      0.1406E+01      0.1122E+03      0.1121E+03      -.3759E+02      -.3725E+02

DELTA(/RAD)               0.2236E-01      0.2236E-01      -.1300E+00      -.1300E+00      0.5388E-01      0.5241E-01
          ------------------------------------------------------

          TRIM ITERATION NUMBER :    2

          SUMMARY  OF  TOTAL  AERODYNAMIC   FORCES  AND  MOMENTS

          MEAN FLOW CONDITION :

          MACH NUMBER                          : 0.700000E+01
          ALTITUDE IN METERS                   : 0.254684E+05
          DYNAMIC PRESSURE IN N/M^2            : 0.813965E+05
          ANGLE OF ATTACK IN DEGREES           : 0.187930E+00
          CONTROL SURFACE DEFLECTION IN DEGREES : 0.500000E+01
```

TRIM VARIABLE: ALPHA = 0.510449E-01(DEG), DELTA = 0.147227E+03(DEG)

FINAL TRIM POSITION: ALPHA = 0.238975E+00(DEG), DELTA = 0.152227E+03(DEG)

AERODYNAMIC STABILITY DERIVATIVES OF FULL SPAN MODEL
REFERENCE AREA = 1.829348 REFERENCE CHORD = 6.267200
X-CG = 3.369830 Z-CG = 6.4264284E-03
TOTAL WEIGHT = 6515.901 NEWTON
X AERODYNAMIC CENTER FROM X = 0 : 7.612310

	DRAG COEFFICIENT		LIFT COEFFICIENT		MOMENT COEFFICIENT	
	RIGID	ELASTIC	RIGID	ELASTIC	RIGID	ELASTIC
MEAN FLOW	0.5802E-01	0.5643E-01	0.9009E-01	0.9007E-01	-.2439E-01	-.2446E-01
ALPHA(/RAD)	0.5685E+01	0.5694E+01	0.3612E+03	0.3611E+03	-.1223E+03	-.1220E+03
DELTA(/RAD)	0.2134E-01	0.2134E-01	-.1262E+00	-.1262E+00	0.5229E-01	0.5181E-01

TRIM ITERATION NUMBER : 3

SUMMARY OF TOTAL AERODYNAMIC FORCES AND MOMENTS

MEAN FLOW CONDITION :

MACH NUMBER : 0.700000E+01
ALTITUDE IN METERS : 0.254684E+05
DYNAMIC PRESSURE IN N/M^2 : 0.813965E+05
ANGLE OF ATTACK IN DEGREES : 0.238975E+00
CONTROL SURFACE DEFLECTION IN DEGREES : 0.500000E+01

TRIM VARIABLE: ALPHA = 0.207079E+00(DEG), DELTA = 0.138391E+03(DEG)

FINAL TRIM POSITION: ALPHA = 0.446054E+00(DEG), DELTA = 0.143391E+03(DEG)

AERODYNAMIC STABILITY DERIVATIVES OF FULL SPAN MODEL
REFERENCE AREA = 1.829348 REFERENCE CHORD = 6.267200
X-CG = 3.369830 Z-CG = 6.4264284E-03
TOTAL WEIGHT = 6515.901 NEWTON
X AERODYNAMIC CENTER FROM X = 0 : 7.593318

	DRAG COEFFICIENT		LIFT COEFFICIENT		MOMENT COEFFICIENT	
	RIGID	ELASTIC	RIGID	ELASTIC	RIGID	ELASTIC
MEAN FLOW	0.5928E-01	0.5770E-01	0.1047E+00	0.1046E+00	-.2801E-01	-.2808E-01
ALPHA(/RAD)	0.3281E+01	0.3290E+01	0.7903E+02	0.7894E+02	-.2663E+02	-.2657E+02
DELTA(/RAD)	0.2107E-01	0.2107E-01	-.1252E+00	-.1252E+00	0.5186E-01	0.5138E-01

TRIM ITERATION NUMBER : 4

SUMMARY OF TOTAL AERODYNAMIC FORCES AND MOMENTS

MEAN FLOW CONDITION :

MACH NUMBER : 0.700000E+01
ALTITUDE IN METERS : 0.254684E+05
DYNAMIC PRESSURE IN N/M^2 : 0.813965E+05
ANGLE OF ATTACK IN DEGREES : 0.446054E+00
CONTROL SURFACE DEFLECTION IN DEGREES : 0.500000E+01

TRIM VARIABLE: ALPHA = 0.232966E+00(DEG), DELTA = 0.129045E+03(DEG)

FINAL TRIM POSITION: ALPHA = 0.679020E+00(DEG), DELTA = 0.134045E+03(DEG)

AERODYNAMIC STABILITY DERIVATIVES OF FULL SPAN MODEL
REFERENCE AREA = 1.829348 REFERENCE CHORD = 6.267200
X-CG = 3.369830 Z-CG = 6.4264284E-03
TOTAL WEIGHT = 6515.901 NEWTON
X AERODYNAMIC CENTER FROM X = 0 : 7.539933

	DRAG COEFFICIENT		LIFT COEFFICIENT		MOMENT COEFFICIENT	
	RIGID	ELASTIC	RIGID	ELASTIC	RIGID	ELASTIC
MEAN FLOW	0.6413E-01	0.6258E-01	0.1072E+00	0.1068E+00	-.2763E-01	-.2756E-01
ALPHA(/RAD)	0.2820E+01	0.2829E+01	0.6247E+02	0.6238E+02	-.2078E+02	-.2074E+02

DELTA(/RAD)	0.1999E-01	0.1999E-01	-.1212E+00	-.1212E+00	0.5016E-01	0.4967E-01

TRIM ITERATION NUMBER : 5

SUMMARY OF TOTAL AERODYNAMIC FORCES AND MOMENTS

MEAN FLOW CONDITION :

```
MACH NUMBER                              : 0.700000E+01
ALTITUDE IN METERS                       : 0.254684E+05
DYNAMIC PRESSURE IN N/M^2                : 0.813965E+05
ANGLE OF ATTACK IN DEGREES               : 0.679020E+00
CONTROL SURFACE DEFLECTION IN DEGREES    : 0.500000E+01
```

TRIM VARIABLE: ALPHA =-0.153836E+01(DEG), DELTA = 0.206640E+03(DEG)

FINAL TRIM POSITION: ALPHA =-0.859338E+00(DEG), DELTA = 0.211640E+03(DEG)

```
AERODYNAMIC STABILITY DERIVATIVES OF FULL SPAN MODEL
REFERENCE AREA =     1.829348      REFERENCE CHORD =     6.267200
X-CG =     3.369830      Z-CG =    6.4264284E-03
TOTAL WEIGHT =     6515.901       NEWTON
X AERODYNAMIC CENTER FROM X = 0 :     7.974348
```

	DRAG COEFFICIENT		LIFT COEFFICIENT		MOMENT COEFFICIENT	
	RIGID	ELASTIC	RIGID	ELASTIC	RIGID	ELASTIC
MEAN FLOW	0.7003E-01	0.6851E-01	0.1152E+00	0.1144E+00	-.2877E-01	-.2858E-01
ALPHA(/RAD)	0.1868E+01	0.1876E+01	-.1461E+02	-.1469E+02	0.5367E+01	0.5363E+01
DELTA(/RAD)	0.1882E-01	0.1882E-01	-.1169E+00	-.1169E+00	0.4835E-01	0.4785E-01

TRIM ITERATION NUMBER : 6

SUMMARY OF TOTAL AERODYNAMIC FORCES AND MOMENTS

MEAN FLOW CONDITION :

```
MACH NUMBER                              : 0.700000E+01
ALTITUDE IN METERS                       : 0.254684E+05
DYNAMIC PRESSURE IN N/M^2                : 0.813965E+05
ANGLE OF ATTACK IN DEGREES               : -.859338E+00
CONTROL SURFACE DEFLECTION IN DEGREES    : 0.500000E+01
```

TRIM VARIABLE: ALPHA = 0.299643E+01(DEG), DELTA = 0.368399E+02(DEG)

FINAL TRIM POSITION: ALPHA = 0.213709E+01(DEG), DELTA = 0.418399E+02(DEG)

```
AERODYNAMIC STABILITY DERIVATIVES OF FULL SPAN MODEL
REFERENCE AREA =     1.829348      REFERENCE CHORD =     6.267200
X-CG =     3.369830      Z-CG =    6.4264284E-03
TOTAL WEIGHT =     6515.901       NEWTON
X AERODYNAMIC CENTER FROM X = 0 :     5.540214
```

	DRAG COEFFICIENT		LIFT COEFFICIENT		MOMENT COEFFICIENT	
	RIGID	ELASTIC	RIGID	ELASTIC	RIGID	ELASTIC
MEAN FLOW	0.7417E-01	0.7235E-01	0.2793E-01	0.2995E-01	-.1361E-01	-.1440E-01
ALPHA(/RAD)	-.1184E+01	-.1168E+01	0.3053E+01	0.2927E+01	-.5287E+00	-.4788E+00
DELTA(/RAD)	0.2741E-01	0.2741E-01	-.1485E+00	-.1485E+00	0.6173E-01	0.6134E-01

TRIM ITERATION NUMBER : 7

SUMMARY OF TOTAL AERODYNAMIC FORCES AND MOMENTS

MEAN FLOW CONDITION :

```
MACH NUMBER                              : 0.700000E+01
ALTITUDE IN METERS                       : 0.254684E+05
DYNAMIC PRESSURE IN N/M^2                : 0.813965E+05
ANGLE OF ATTACK IN DEGREES               : 0.213709E+01
CONTROL SURFACE DEFLECTION IN DEGREES    : 0.500000E+01
```

TRIM VARIABLE: ALPHA = 0.767660E+00(DEG), DELTA = 0.343145E+02(DEG)

FINAL TRIM POSITION: ALPHA = 0.290475E+01(DEG), DELTA = 0.393145E+02(DEG)

```
-----------------------------------------------------
AERODYNAMIC STABILITY DERIVATIVES OF FULL SPAN MODEL
REFERENCE AREA =    1.829348      REFERENCE CHORD =     6.267200
X-CG =     3.369830      Z-CG =   6.4264284E-03
TOTAL WEIGHT =     6515.901      NEWTON
X AERODYNAMIC CENTER FROM X = 0 :  -0.4764185
```

	DRAG COEFFICIENT		LIFT COEFFICIENT		MOMENT COEFFICIENT	
	RIGID	ELASTIC	RIGID	ELASTIC	RIGID	ELASTIC
MEAN FLOW	0.1132E+00	0.1118E+00	0.1372E+00	0.1347E+00	-.2655E-01	-.2557E-01
ALPHA(/RAD)	0.2213E+01	0.2216E+01	0.6787E+00	0.6240E+00	0.2083E+00	0.2288E+00
DELTA(/RAD)	0.1249E-01	0.1249E-01	-.9269E-01	-.9269E-01	0.3819E-01	0.3758E-01

```
-----------------------------------------------------

TRIM ITERATION NUMBER :   8

SUMMARY  OF  TOTAL  AERODYNAMIC   FORCES  AND  MOMENTS

MEAN FLOW CONDITION :

MACH NUMBER                           : 0.700000E+01
ALTITUDE IN METERS                    : 0.254684E+05
DYNAMIC PRESSURE IN N/M^2             : 0.813965E+05
ANGLE OF ATTACK IN DEGREES            : 0.290475E+01
CONTROL SURFACE DEFLECTION IN DEGREES : 0.500000E+01

TRIM VARIABLE: ALPHA =-0.392802E-01(DEG), DELTA = 0.423029E+02(DEG)

FINAL TRIM POSITION: ALPHA = 0.286547E+01(DEG), DELTA = 0.473029E+02(DEG)

-----------------------------------------------------
AERODYNAMIC STABILITY DERIVATIVES OF FULL SPAN MODEL
REFERENCE AREA =    1.829348      REFERENCE CHORD =     6.267200
X-CG =     3.369830      Z-CG =   6.4264284E-03
TOTAL WEIGHT =     6515.901      NEWTON
X AERODYNAMIC CENTER FROM X = 0 :     3.921978
```

	DRAG COEFFICIENT		LIFT COEFFICIENT		MOMENT COEFFICIENT	
	RIGID	ELASTIC	RIGID	ELASTIC	RIGID	ELASTIC
MEAN FLOW	0.1419E+00	0.1406E+00	0.1525E+00	0.1493E+00	-.2575E-01	-.2449E-01
ALPHA(/RAD)	0.2804E+01	0.2806E+01	0.1737E+01	0.1695E+01	-.7652E-01	-.6039E-01
DELTA(/RAD)	0.9796E-02	0.9796E-02	-.8205E-01	-.8205E-01	0.3372E-01	0.3311E-01

```
-----------------------------------------------------

TRIM ITERATION NUMBER :   9

SUMMARY  OF  TOTAL  AERODYNAMIC   FORCES  AND  MOMENTS

MEAN FLOW CONDITION :

MACH NUMBER                           : 0.700000E+01
ALTITUDE IN METERS                    : 0.254684E+05
DYNAMIC PRESSURE IN N/M^2             : 0.813965E+05
ANGLE OF ATTACK IN DEGREES            : 0.286547E+01
CONTROL SURFACE DEFLECTION IN DEGREES : 0.500000E+01

TRIM VARIABLE: ALPHA =-0.188472E-02(DEG), DELTA = 0.419849E+02(DEG)

FINAL TRIM POSITION: ALPHA = 0.286359E+01(DEG), DELTA = 0.469849E+02(DEG)

-----------------------------------------------------
AERODYNAMIC STABILITY DERIVATIVES OF FULL SPAN MODEL
REFERENCE AREA =    1.829348      REFERENCE CHORD =     6.267200
X-CG =     3.369830      Z-CG =   6.4264284E-03
TOTAL WEIGHT =     6515.901      NEWTON
X AERODYNAMIC CENTER FROM X = 0 :     4.162561
```

	DRAG COEFFICIENT		LIFT COEFFICIENT		MOMENT COEFFICIENT	
	RIGID	ELASTIC	RIGID	ELASTIC	RIGID	ELASTIC
MEAN FLOW	0.1400E+00	0.1387E+00	0.1512E+00	0.1481E+00	-.2568E-01	-.2442E-01
ALPHA(/RAD)	0.2762E+01	0.2764E+01	0.1795E+01	0.1753E+01	-.1135E+00	-.9710E-01
DELTA(/RAD)	0.9925E-02	0.9925E-02	-.8256E-01	-.8256E-01	0.3394E-01	0.3332E-01

```
-----------------------------------------------------

TRIM ITERATION NUMBER :  10
```

```
SUMMARY  OF  TOTAL  AERODYNAMIC   FORCES  AND  MOMENTS

MEAN FLOW CONDITION :

MACH NUMBER                          : 0.700000E+01
ALTITUDE IN METERS                   : 0.254684E+05
DYNAMIC PRESSURE IN N/M^2            : 0.813965E+05
ANGLE OF ATTACK IN DEGREES           : 0.286359E+01
CONTROL SURFACE DEFLECTION IN DEGREES : 0.500000E+01


TRIM VARIABLE: ALPHA =-0.209324E-03(DEG), DELTA = 0.419760E+02(DEG)


FINAL TRIM POSITION: ALPHA = 0.286338E+01(DEG), DELTA = 0.469760E+02(DEG)

-----------------------------------------------------
 AERODYNAMIC STABILITY DERIVATIVES OF FULL SPAN MODEL
 REFERENCE AREA =    1.829348      REFERENCE CHORD =     6.267200
 X-CG =     3.369830       Z-CG =    6.4264284E-03
 TOTAL WEIGHT =     6515.901      NEWTON
 X AERODYNAMIC CENTER FROM X = 0 :     4.011549
```

	DRAG COEFFICIENT		LIFT COEFFICIENT		MOMENT COEFFICIENT	
	RIGID	ELASTIC	RIGID	ELASTIC	RIGID	ELASTIC
MEAN FLOW	0.1399E+00	0.1386E+00	0.1512E+00	0.1480E+00	-.2568E-01	-.2442E-01
ALPHA(/RAD)	0.2751E+01	0.2754E+01	0.1718E+01	0.1676E+01	-.8795E-01	-.7123E-01
DELTA(/RAD)	0.9931E-02	0.9931E-02	-.8258E-01	-.8258E-01	0.3395E-01	0.3333E-01

```
-----------------------------------------------------

FINAL TRIM ANGLE OF ATTACK IN DEGREES =  0.286338E+01
FINAL TRIM DELTA IN DEGREES =  0.469760E+02

-----------------------------------------------------
```

Listing 9.8.6 Prep_ASE.dat

A Matrix:

	1	2	3	4	5	6	7	8	9	10
1	0.0000E+00	1.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
2	0.0000E+00	-1.5029E-02	0.0000E+00	-2.8752E+02	-9.8067E+00	-8.5328E-02	4.8194E+00	4.8070E+00	6.6040E-09	-2.5374E-09
3	0.0000E+00	0.0000E+00	0.0000E+00	-2.0909E+03	2.0909E+03	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
4	0.0000E+00	-7.7600E-06	0.0000E+00	-1.0141E-01	-2.1371E-09	9.9999E-01	-9.4810E-13	-9.4787E-13	3.4793E-11	4.6974E-12
5	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	1.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
6	0.0000E+00	-1.2192E-03	0.0000E+00	-5.1129E+00	1.5581E-07	-3.1123E-02	4.4854E-02	4.5135E-02	-5.5019E-08	-1.2848E-08
7	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	1.0000E+00	0.0000E+00
8	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	1.0000E+00
9	0.0000E+00	3.7082E-02	0.0000E+00	3.7481E+02	-7.4961E+02	-5.3790E-02	-1.4471E+02	-3.1946E-08	-2.4324E-03	-4.2473E-06
10	0.0000E+00	3.5547E-01	0.0000E+00	1.6674E+03	-3.3349E+03	3.0120E-01	-4.3638E-08	-1.0332E+03	-4.2653E-06	-6.4571E-03

B matrix:

```
  0.000000E+00
 -0.111283E+01
  0.000000E+00
  0.442585E-02
  0.000000E+00
  0.168089E+01
  0.000000E+00
  0.000000E+00
 -0.160677E+03
  0.861835E+02
```

Eigenvalues of A:

```
(0.0000000E+00,0.0000000E+00)
(0.0000000E+00,0.0000000E+00)
(-4.0625930E-03,32.14232)
(-4.0625930E-03,-32.14232)
```

```
(-1.8121749E-03,12.02456)
(-1.8121749E-03,-12.02456)
(-9.8287821E-02,2.304482)
(-9.8287821E-02,-2.304482)
(6.4862937E-02,0.0000000E+00)
(-1.2984279E-02,0.0000000E+00)

Damping Ratio (Zeta) and Frequency (Omega)
Zeta : -1.2639390E-04 Omega :   5.113551     Hz
Zeta : -1.5070618E-04 Omega :   1.912998     Hz
Zeta : -4.2611990E-02 Omega :  0.3669554     Hz
Zeta :   1.000000     Omega :  1.0319103E-02 Hz
Zeta :  -1.000000     Omega :  2.0656807E-03 Hz

Output Prepared for Analytical Solution of Flight Dynamic Model
-------------------------

Mass (m) =                     1328.874
Velocity (U) =                 2090.866
Surface Area (S) =             1.829348
Dynamic Pressure (q) =         81396.51
Moment of Inertia (Iyy) =      18848.73
Reference Length (c) =         6.267200
Cd wrt u (Cdu) =              2.9367459E-04
Cm wrt u (Cmu) =             -6.6151595E-05
Cl wrt u (Clu) =              1.9072900E-04

Cd wrt q (Cdq) =              0.5058688
Cm wrt q (Cmq) =             -4.5670047E-02
Cl wrt q (Clq) =              0.1237800

Cd wrt alpha (Cd_alpha) =      2.717112
Cm wrt alpha (Cm_alpha) =    -0.1032690
Cl wrt alpha (Cl_alpha) =      1.752287

Coefficient of drag (Cd) =    0.1399257
Coefficient of moment(Cm)=   -2.5678078E-02
Coefficient of lift (Cl) =    0.1511889
```

9.9 Subsequent Design Cycles for Converged Configuration

The trim angle of attack obtained from the TRIM analysis may not agree with the initially guessed design angle of attack specified in the UCDA input file vehicle.inp with the parameter AOADES. In order to match these two angles of attack, it is required to perform multiple design cycles by repeating the entire cycle described in Sections 9.1 through 9.8. For each new design cycle, the parameter AOADES is updated by the trim angle of attack computed by the previous design cycle. This multiple design cycle process terminates when the variation between AOADES and trim angle of attack becomes small; leading to a converged configuration.

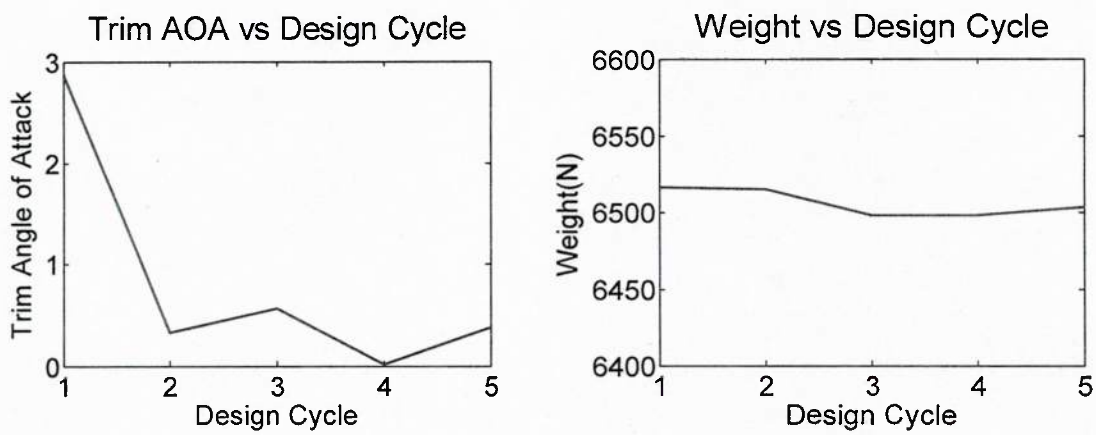

Figure 9.9.1 Convergence History of Angle of Attack and Weight for SED Vehicle

For the present SED configuration, it is found that this converged configuration is obtained after three design cycles. Figure 9.9.1 shows the trim angle of attack, control surface deflection angle and weight at each design cycle. It can be seen that at the third design cycle, the trim angle of attack is nearly converged at 0.5668 degrees and the weight is converged at 6498 Newton respectively.

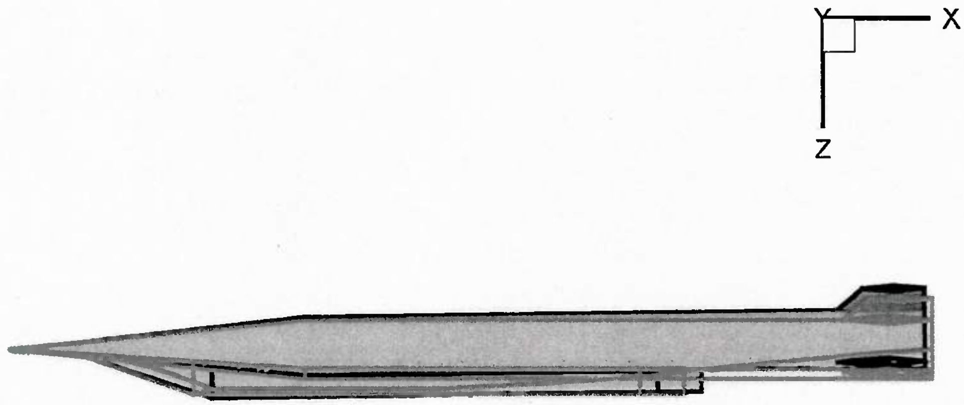

Figure. 9.9.2 Comparison of the SED vehicle between first and final design cycles

Figure 9.9.2 shows the comparison of the vehicle geometry between first design cycle and the last design cycle. It can be seen that for the first design cycle, the vehicle had a higher negative design angle of attack. That made the ramp angle shallower and thus in order to satisfy shock-on-lip condition, the inlet of the combustor was pushed downstream by the design. On the other hand, for the final converged design, the design angle of attack is larger. Thus, to satisfy shock-on-lip condition, the inlet of the combustor is pushed upstream.

The result of the SED configuration suggests that this multiple design cycle process is a viable method to design such a vehicle even though there is not solid theoretical foundation to guarantee such a convergence at present.

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